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Air Quality in Intercity Coaches

Prepared for the
Transportation Development Centre
Policy and Coordination Group
Transport Canada

by

DELCAN ENGINEERS PLANNERS ARCHITECTS
in association with
TES Limited
Concord Scientific Corporation

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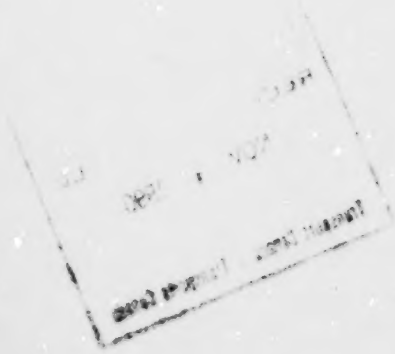

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16. Abstract

Air quality is an important consideration for intercity coach operators in terms of passenger comfort, and it has a significant effect on customer satisfaction. The objective of this research is to study the critical problems relating to air distribution and air cleanliness in conventional Canadian coaches and to objectively and quantitatively assess the existing comfort levels of passengers. The interior aerodynamics of conventional coaches were accurately characterized by measuring: distribution of outdoor air and recycled air; ambient flow velocities and ventilation system volume flow rates; air-flow patterns in the passenger compartment, including an investigation of the effects of passenger occupancy, highway speeds and the driver's air conditioning system and window; temperature distributions in the coach during heating and cooling; particle residence times for pollutants located at various positions in the coach; and air concentrations of cigarette smoke near the source, in the supply air, and in the exhaust air. Several indicators of air quality were monitored during normal intercity operation on non-smoking and smoking runs. Selected indicators of air quality comprised respirable particulate, carbon dioxide, temperature and relative humidity. Key results include: maximum outdoor air component was 8 to 9% of supply air (4 to 5 cfm/person); ambient air velocities ranged from 20 to 110 fpm; air supply and return configurations which cause ambient air to flow through several rows of seats, left to right side supply air imbalance from 17% to 37%; effect of one cigarette anywhere in the coach was noticeable at the exhaust in under two minutes; existing filters are unable to capture cigarette smoke; carbon dioxide concentrations exceeded 1700 ppm with full passenger loads. Suggested alternatives to improve air quality include: double or triple outdoor air portion; improve filtration; eliminate smoking.

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16. Résumé

La qualité de l'air à l'intérieur des autocars est une préoccupation majeure des exploitants du fait qu'elle ajoute beaucoup à la satisfaction et au confort des passagers. La recherche entreprise a visé le double but d'approfondir les aspects critiques relatifs à la qualité de l'air et à sa distribution à l'intérieur des autocars courants et de mesurer de manière objective les niveaux de confort dont bénéficient les passagers. Le contrôle des paramètres suivants a permis de caractériser avec précision les qualités essentielles de la circulation de l'air à l'intérieur des autocars de type courant: la proportion d'air neuf et d'air recyclé; les vitesses des flux d'air dans le compartiment passagers, et les débits volumiques des systèmes de ventilation; les mouvements de l'air dans le compartiment passagers et l'effet produit par les variations dans le nombre de passagers, par la vitesse de l'autocar et par la mise en marche de la climatisation ou l'ouverture de la fenêtre dans le poste de conduite; la répartition des températures dans ce compartiment lorsqu'il est chauffé out climatisé; la durée de présence des polluants en divers endroits et la concentration des fumées de tabac à proximité des fumeurs, dans l'air fourni et dans l'air évacué. Parmi les indicateurs de la qualité de l'air contrôlés en divers endroits et en exploitation normale dans des autocars fumeurs et non fumeurs, figurent la concentration de particules inhalables et d'anhydride carbonique, la température et l'humidité relative. Les principaux résultats obtenus de cette recherche on été les suivants: proportion maximum d'air neuf dans l'air fourni: 8 à 9 p.100 (4 à 5 pi³ par minute et par personne); vitesse de l'air dans le compartiment: entre 20 et 110 pi/min; les circuits d'air fourni et d'air évacué qui font circuler l'air entre plusieurs rangées des sièges induisent un écart dans le débit d'air fourni, côté gauche et côté droit: de 17 à 37 p. 100; l'effet d'une cigarette fumée n'importe où dans l'autocar se fait sentir dans l'air évacué en moins d'une ou de deux minutes; les filtres existants ne réussissent pas à intercepter la fumée de cigarette; la concentration d'anhydride carbonique dépasse 1 700 p.p.m. lorsque tous les sièges ont occupés. Doubler ou tripler la proportion d'air neuf,améliorer le filtrage et interdire le tabagisme, telles ont été les principales recommandations pour améliorer la qualité de l'air.

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SUMMARY

Air quality is an important consideration for intercity coach operators in terms of passenger comfort and has a significant effect on customer satisfaction. A significant improvement in environmental comfort would make highway bus transportation more attractive and thereby improve the health of the carrier industry, reduce total transportation costs and encourage greater public use of this efficient mode.

The objective of this research is to study the critical problems relating to air distribution and cleanliness in conventional Canadian coaches and to assess existing comfort levels of passengers objectively and quantitatively.

There is little recent serious research on air quality in buses. Previous research work specifically related to air quality in intercity coaches is limited to a previous study undertaken by Transport Canada and a study initiated by Voyageur Inc., a carrier operating over 300 vehicles. Both these efforts recognized second-hand smoke and a lack of outdoor air as key elements that compromise comfort/health in conventional coaches. The Transport Canada study suggested the current, more in-depth research effort as a medium-term goal.

The test program concentrated on the MCI, MC9 and the Prévost Marathon XL coaches. To ensure that the results would have wide applicability, part of the test program involved a comparison of coaches of the same model type. This permitted an evaluation of the variability in coach air-conditioning system performance, since the degree of variability could have a significant influence on the test results.

The interior aerodynamics of conventional coaches were accurately characterized by measuring the following parameters:

- the distribution of fresh air and recycled air supplied to the passenger compartment;
- flow velocities and volume flow rates in the passenger compartment and air conditioning system;
- overall air flow patterns in the passenger compartment including an investigation of the effects of passenger occupancy, highway speeds and the driver's air conditioning system and window;
- temperature distributions in the coach during heating or cooling;
- particle residence times for pollutant sources located at various positions in the coach;

- air concentrations of cigarette smoke near the source, in the supply air and in the exhaust air.

Several indicators of air quality were monitored at numerous locations throughout the coach during normal intercity operation on smoking and non-smoking runs. Selected indicators of air quality comprised respirable particulate, carbon dioxide, temperature and relative humidity.

Two measurement methods for respirable particulate were used. The first utilized a pre-calibrated, battery-operated pump that draws air at a known, constant rate through a pre-weighed, teflon, 37 mm diameter filter. Upon completion of sampling, the filter was analyzed gravimetrically to determine weight gain during a known sampling period. The second method involved real-time analysis of airborne respirable particulate, using the Sibata digital dust indicator. This instrument determines relative concentrations of airborne particulate by measuring the intensity of light scattered by particulate passing through an illumination chamber.

Carbon dioxide concentrations were monitored using two different sampling methods, both giving instantaneous readout. The first was the Horiba portable carbon dioxide monitor, which determines carbon dioxide concentrations by infrared analysis. The second was Gastec Analyzer tubes, which develop a length of stain in proportion to the concentration of carbon dioxide in the sampled air. The two methods were used simultaneously, as a check on analytical results.

Temperature and relative humidity were monitored using dry and wet bulb thermometers.

The foregoing measurement effort produced the following key results:

- Outdoor air component of 8 to 9% of air supplied to passenger compartment (4 to 5 cfm/person).

- Air velocities inside the passenger compartment ranging from 20 to 110 fpm.

- Air supply and return configurations causing passenger compartment air to flow through several rows of seats.

- Left to right side supply air imbalance: side to side flow differences of 17 to 37%.

- The effect of one cigarette anywhere in the coach was noticeable at the exhaust in under one or two minutes.

- Smoke concentrations in supply air were similar to or slightly less than concentrations in exhaust air. This suggests completely ineffective filtering.

- Respirable particulate concentrations of about 12 $\mu g/m^3$ during actual non-smoking runs, and average concentrations in the range of 70 to 100 $\mu g/m^3$ during actual smoking runs. One-third of the readings exceeded 100 $\mu g/m^3$.

- Carbon dioxide levels consistently exceeded 1000 ppm and concentrations of 1700 ppm or higher were associated with full passenger loads.

- Temperature and humidity were largely within an acceptable range.

Target air quality parameters were developed which, if achieved, would ensure a very comfortable passenger environment. The five comfort parameters were defined as follows:

Temperature:	20°C to 25°C
Humidity:	40% to 60% RH
Interior Air Speeds:	20 to 50 fpm
Respirable Particulate:	less than 100 $\mu g/m^3$
Carbon Dioxide:	less than 1000 ppm.

Key variables and physical limitations of a coach heating, ventilating and air conditioning system were explored to better appreciate the process any alternatives to improve comfort would attempt to modify.

The practical implications of increasing dilution air to satisfy the target air quality parameters above was explored in some detail. Modifications to existing conventional coaches would involve the addition of optional diesel-fuelled water heaters to complement engine heat, changes to outdoor air intakes and exhaust outlets to reduce flow restrictions, and possibly the addition of a flow sensitive control device on the exhaust outlet to maintain sufficient positive pressure within the vehicle.

More efficient filtration options of both high and low capacity were discussed outlining advantages and disadvantages of each. Research on aircraft has shown that the high efficiency filtration systems currently in use on modern passenger airliners equipped with recirculation systems have substantially reduced irritation associated with tobacco smoke. Unfortunately, these filters require much more space than that currently available on North American coaches.

Complaints of drafts could be reduced by more careful balancing of supply and return air in existing coaches. Alternatives that would help reduce interior air velocities on next generation coaches would include: reducing heating and

cooling loads by better insulating the bus envelope; reducing solar loads by selecting more reflective glazing systems and a vented roof skin; and establishing a radiant heating system near the perimeter.

The effects of eliminating smoking on air quality and comfort in coaches would be very significant. Prohibiting smoking would also reduce cleaning costs, and the costs of replacing or repairing damaged materials.

A ban on smoking would reduce irritation and health risks, and completely satisfy the target comfort parameter associated with respirable particulate.

Besides the conclusions related to results of the measurement program listed above, it was concluded that a compact, high-performance, economical filter system that effectively removes gases and particles associated with tobacco smoke, and is compatible with requirements for installation on existing coaches, has not yet been developed.

Recommendations included operating existing coaches to maximize dilution, and increasing intake and exhaust air flows to satisfy 1000 ppm carbon dioxide concentration (about 15 cfm per passenger).

If comfort is to be achieved while smoking is permitted, special filtration systems should be developed to suit coach requirements. In addition, the smoking section should be located in the front of MC9 coach and in the centre of the Marathon XL coach, to minimize the effect of second-hand smoke on non-smoking passengers. More space should be allocated for filtration systems to permit the installation of filtration systems similar to those in use on some modern aircraft.

SOMMAIRE

La qualité de l'air à l'intérieur des autocars est une préoccupation majeure des exploitants du fait qu'elle ajoute beaucoup à la satisfaction et au confort des passagers. En améliorant la qualité de l'ambiance à l'intérieur des autocars, ils espèrent en accroître l'attractivité, relever la rentabilité de l'exploitation, réduire les coûts et attirer de la sorte encore plus de clients.

La recherche entreprise a visé le double but d'approfondir les aspects critiques relatifs à la qualité de l'air et à sa distribution à l'intérieur des autocars courants et de mesurer de manière objective les niveaux de confort dont bénéficient les passagers.

Peu d'études sérieuses ont été faites récemment sur cette question. Les seules ayant trait spécifiquement à la qualité de l'air dans les autocars on été celles de Transports Canada et de Voyageur Inc., qui exploite plus de 300 autocars. Ces deux études sont arrivées à la conclusion que les deux éléments qui compromettent le plus le confort et la santé des passagers sont la fumée secondaire indirecte et l'insuffisance d'air neuf. Quant à l'étude de Transports Canada, elle a débouché sur la présente recherche, la plus approfondie de toutes.

La recherche s'est concentrée sur les autocars MCI, MC9 et Prévost modèle Marathon XL. Afin de ne pas limiter la portée des résultats, le programme d'essais prévoyait la comparaison d'autocars de même modèle. Cette façon de procéder a permis de vérifier les variations de rendement dans la climatisation d'un autocar à l'autre, facteur qui peut avoir une grande influence sur les résultats finals.

Le contrôle des paramètres suivants a permis de caractériser avec précision la circulation de l'air à l'intérieur des autocars de type courant:

- la proportion d'air neuf et d'air recyclé entrant dans le compartiment passagers;
- les vitesses et les débits volumiques de l'air dans ce compartiment et dans le système de climatisation;
- les mouvements de l'air dans ce compartiment et l'effet produit par les variations dans le nombre de passagers, par la vitesse de l'autocar et par la mise en marche de la climatisation ou l'ouverture de la fenêtre dans le poste de conduite;
- la répartition des températures dans ce compartiment lorsqu'il est chauffé ou climatisé;
- durée de présence des polluants en divers endroits;

- concentration des fumées de tabac à proximité des fumeurs, dans l'air fourni et dans l'air évacué.

Parmi les indicateurs de la qualité de l'air, contrôlés en divers endroits et en exploitation normale dans des autocars fumeurs et non fumeurs, figurent la concentration de particules inhalables et d'anhydride carbonique, la température et l'humidité relative.

Le mesurage des concentrations de particules inhalables s'est fait selon deux méthodes. La première faisait appel à une pompe électrique étalonnée aspirant l'air à un débit constant à travers un filtre en téflon, de poids connu et de 37 mm de diamètre. Ce filtre était pesé à la fin de chaque période d'échantillonnage afin de déterminer le poids des particules déposées. La seconde utilisait l'appareil numérique Sibata qui analyse en temps réel la concentration des particules inhalables en suspension dans l'air. Il comporte un réflectomètre qui mesure l'intensité de la lumière diffusée par les particules en suspension.

Quant à l'anhydride carbonique, sa concentration a été mesurée suivant deux techniques d'échantillonnage produisant des lectures instantanées.

La première faisant appel à l'analyseur portatif Horiba, du type à absorption dans l'infrarouge, et la second à des tubes analyseurs Gastec qui développent une longueur de coloration proportionnelle à la concentration de ce gaz dans l'échantillon. Ces deux techniques, utilisées parallèment, ont servi à contrôler le résultat des méthodes analytiques.

Un psychromètre a servi au contrôle de la température et de l'humidité relative.

Les principaux résultats obtenus de cette recherche ont été les suivants:

- proportion maximum d'air neuf dans l'air fourni: de 8 à 9 p. 100 (de 4 à 5 pi^3 par minute et par personne).

- vitesse de l'air dans le compartiment: entre 20 et 110 pi/min;

- les circuits d'air fourni et d'air évacué font circuler l'air entre plusieurs rangées de sièges;

- écart dans le débit d'air fourni, côté gauche et côté droit: de 17 à 37 p. 100;

- l'effet d'une cigarette fumée n'importe où dans l'autocar se fait sentir dans l'air évacué en moins d'une ou de deux minutes;

- la concentration de fumée dans l'air fourni et dans l'air évacué a été trouvée plus ou moins égale, indiquant une filtration peu efficace;

- concentration de particules inhalables: 12 $\mu g/m^3$ environ en parcours où il est interdit de fumer et une moyenne entre 70 et 100 $\mu g/m^3$ lorsqu'il a été permis de fumer. La valeur de 100 $\mu g/m^3$ a été dépassée dans un tiers des cas;

- concentration d'anhydride carbonique: supérieure à 1 000 p.p.m., atteignant ou dépassant 1 700 p.p.m. lorsque tous les sièges étaient occupés;

- la température et le taux d'humidité ont presque toujours été à l'intérieur des limites admissibles.

La recherche a permis de cerner la plage des valeurs que devraient occuper les cinq paramètres de qualité de l'air afin d'assurer une ambiance confortable. Ce sont les suivantes:

Température:	de 20 à 25 °C
Humidité Relative:	de 40 à 60 p. 100
Vitesse de l'air intérieur:	de 20 à 50 pi/min
Particules inhalables:	moins de 100 $\mu g/m^3$
Anhydride carbonique:	moins de 1 000 p.p.m.

Les principaux paramètres ainsi que les contraintes matérielles concernant les systèmes de chauffage, ventilation et climatisation ont été approfondis dans le but de cerner de plus près les phénomènes en jeu que les solutions de rechange visent à améliorer.

Les aspects pratiques d'un taux de dilution accru dans le but de satisfaire aux normes ci-dessus ont été approfondis. Les modifications envisagées dans les autocars courants sont: installer des chauffe-eau à carburant diesel pour suppléer à l'insuffisance du chauffage fourni par le moteur; modifier la forme des prises d'air neuf et des sorties d'air évacué pour améliorer l'écoulement de l'air et, peut-être aussi, adapter aux sorties d'air évacué un dispositif sensible au débit d'air de manière à conserver à l'intérieur de l'autocar une pression positive suffisante.

Les chercheurs ont examiné diverses options de filtrage haut et faible débit susceptibles d'accroître l'efficacité des systèmes actuels; ils ont aussi établi les avantages et les inconvénients de chacune. La recherche sur les systèmes de filtration haut rendement à circuit de recirculation utilisés à bord des avions de ligne modernes a montré qu'ils réussissent à arrêter la plus grande partie des irritants contenus dans la fumée du tabac, mais que, malheureusement, leur encombrement est de beaucoup supérieur à celui autorisé par les autocars de construction courante en Amérique du Nord.

Les courants d'air dont se plaignent les passagers peuvent être atténués par un meilleur équilibrage entre air fourni et air repris. Les solutions possibles dans les nouvelles familles d'autocars pourraient être les suivantes: meilleure isolation

pour réduire l'intensité des transferts thermiques; choix de vitrages plus réfléchissants et ventilation du pavillon pour combattre l'apport de chaleur par l'insolation et système de chauffage par rayonnement installé en périphérie.

L'interdiction de fumer à bord des autocars aurait un effet considérable sur la qualité de l'air et sur le confort général, sans oublier le fait que les coûts de nettoyage et de remplacement ou de réparation des articles endommagés seraient moindres.

Elle aurait aussi pour effet de réduire la concentration d'irritants, d'assainir l'atmosphère et de satisfaire à la norme de confort touchant les particules inhalables.

La recherche a abouti à une autre conclusion, à savoir qu'il n'existe pas encore de filtres à la fois compacts, efficaces et économiques qui, en plus de bloquer les gaz et les particules dus au tabagisme, aient le faible encombrement que permettent les autocars de construction courante.

Parmi les recommandations formulées, il y a celle de satisfaire à la norme d'une concentration d'anhydride carbonique maximale de 1 000 p.p.m. en maximisant le taux de dilution et en augmentant les débits d'air extérieur et d'air évacué (quelque 15 pi^3 par minute et par personne).

Si l'option d'interdire le tabagisme ne peut être retenue, alors il faudra étudier des systèmes de filtration particuliers adaptables aux autocars. De plus, le compartiment fumeurs devra être placé à l'avant des MC9 et au centre du Marathon modèle XL, afin que les passagers non fumeurs soient les moins possible incommodés par la fumée secondaire indirecte. Enfin, il faudra prévoir à bord suffisamment d'espace pour recevoir des systèmes de filtration semblables à ceux de certains avions de ligne.

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1.0 INTRODUCTION

1.1 Purpose and Objective

Air quality is an important consideration in terms of passenger comfort and has an effect on customer satisfaction. A significant improvement in environmental comfort would make highway bus transportation more attractive and thereby improve the health of the carrier industry, reduce total transportation costs and encourage greater public use of this efficient mode.

The objective of this research is to study the critical problems relating to air conditioning, i.e., air cleanliness and distribution, in conventional coaches and to quantitatively assess existing comfort levels of passengers. To prepare detailed recommendations on concrete solutions to be studied in a subsequent phase.

1.2 State of the Art

In response to a request from Voyageur, the Transportation Development Centre (TDC) of Transport Canada carried out an investigative study as part of its research program on improvements to conventional buses. The purpose of this November 1985 study entitled "Improved Air Quality in Intercity Buses", was to provide a general evaluation of air quality in buses. The results of this investigative study confirm the proposals made by Centre de Recherche Industrielle du Québec (CRIQ) in 1982 which included increasing the outdoor air component and incorporating improved filtration. More specifically, this 1985 investigative study concluded that the outdoor air component in conventional bus ventilation systems should be doubled and that electrostatically augmented filtration technology should be demonstrated. It also strongly recommended that ionizing type air cleaners with no capacity for dust collection not be considered since their performance is unsatisfactory owing to the fact they contribute to the embedding of ambient dust in the seats and throughout the bus.

In terms of further research, the 1985 investigative study suggested the present quantitative assessment of air cleanliness and distribution.

1.3 Structure of Study

The first step involved the characterization of air flow in intercity coaches. Before detailed tests were developed the "conventional coach" required definition. Following a number of qualitative and quantitative tests, an extensive battery of tests were developed to detail air flow distribution characteristics of two representative models of intercity coach. These tests involved the measurement and illustration of air volume flow rates, air speed and direction at discreet locations, general air flow patterns within the coach, ventilation system balance, outdoor air distribution and particle residence times. A description of the above process and the discussion of results is documented in Chapter 2 and Appendix A.

Chapter 3 reports on tasks performed to determine air concentrations of cigarette smoke near the source, in the supply air, and in the exhaust air. Measurements were made on both representative models of coach.

Chapter 4 documents air quality variations in smoking and non-smoking buses. Several indicators of air quality were monitored at numerous locations throughout the bus during normal intercity operation. Parameters that were monitored are respirable particulate, carbon dioxide, temperature and relative humidity. These parameters were selected because of their association with passenger comfort, occupancy levels and smoking.

In Chapter 5 the general problem statement is described by briefly stating key results of the measurement program carried out in Chapters 2, 3 and 4.

Chapter 5 goes on to define air quality parameters in terms of quantitative limits on: temperature, humidity, interior air speeds, respirable particulate and carbon dioxide. Prior to the development of alternatives, a schematic and simplified mathematical model of the HVAC process is developed in order to better understand the variables and parameters associated with the coach comfort system.

Finally, Chapter 5 closes out with a description of alternatives which would improve air quality in coaches and could be developed further in subsequent work.

Chapter 6 summarizes the findings in the form of conclusions and recommendations.

2.0 AIR FLOW CHARACTERIZATION

To obtain the air flow distribution characteristics in the test coaches, a number of qualitative and quantitative tests were conducted. These tests involved the measurement and illustration of air volume flow rates, air speed and direction at discrete locations, general air flow patterns within the coach, ventilation system balance, fresh air distribution and particle residence times.

This section presents a summary of the work conducted to determine the air flow distribution characteristics of intercity coaches. A more detailed report prepared by TES Limited is included in Appendix A.

2.1 Test Objectives

The overall objective of the test program was to determine the air flow distribution characteristics of intercity buses. This broad objective can be defined by a set of more detailed objectives, as follows:

1. Determine the distribution of fresh air and recycled air supplied to the passenger compartment.
2. Determine flow velocities and volume flow rates in the passenger compartment and in the air conditioning system.
3. Determine the air flow patterns in the passenger compartment including an investigation of the effects of passenger occupancy, highway speeds and the driver's air conditioning system and window.
4. Determine temperature distributions in the coach during heating or cooling.
5. Determine particle residence times for pollutant sources located at various positions in the coach.

To attain these objectives, a complete understanding of the operation of the coach air conditioning system is required. Since the coach air conditioning systems generally have the capacity to completely recirculate the air inside the bus within one minute, the air flow patterns are quite complex. In addition, each

coach has a multitude of settings and adjustments which can be used to fine tune the coach environment and this increases the complexity of the bus air flow characteristics. The following section discusses the various parameters which were taken into account during the test program.

2.2 Test Parameters

In intercity buses, there are generally many controls which allow air flows and temperatures to be adjusted and which permit varying amounts of fresh air to be introduced into the bus. With the existence of two independent air conditioning systems in most buses (the driver's system and the passenger compartment system), many combinations of air flows and temperatures are available.

The driver's air conditioning system recirculates air in the front portion of the bus. The recirculated air is conditioned using a heating coil and an evaporator and an adjustable damper allows fresh air to be mixed with the recirculated air. Fresh air is introduced into the system via a vent located under the front windshield. The fresh air damper is normally closed so that the driver is supplied with recirculated air only. A gasper, which is fed with conditioned air from the driver's system, is located in the immediate vicinity of the driver. On some bus models there is a second gasper which can be used to supply (unconditioned) fresh air directly to the driver. On most models, the driver's air conditioning system has a fan speed control and a temperature control and the system can be switched for defroster operation when required. Another option available to the driver is the positioning of the side window. If this window is open, local air flow patterns may be significantly influenced.

The passenger compartment air conditioning and ventilation system can be operated in a heating or cooling mode and the temperature setting is fully adjustable in either mode. The fresh air intake is adjustable by means of a damper and in some buses there is an exhaust vent in the front door which can be operated from a fully open to a fully closed position. In the washroom located at the rear of the coach, there is a window which can be opened or closed, thus

causing local changes in the air flow. In addition, the washrooms are vented through the holding tank to prevent any odours from entering the passenger compartment.

Other parameters which were taken into consideration, although not directly related to the operation of the air conditioning systems, include the effects of passenger occupancy and the influence of highway speeds on the air flow characteristics within the coach.

Before defining any specific tests or test procedures, the representative test coaches to be used were determined. A review of the air distribution systems on various intercity coaches indicated that they do not use generically similar systems. For example, the return air porting on the buses was found to be quite different. Prévost Car Inc. models introduce fresh air into the air conditioning system via a single port on the curbside and return air through a single floor duct located centrally on the left hand side of the bus. Motor Coach Industries (MCI), on the other hand, introduce fresh air via two ports, one on each side, and return air through a wall plenum, ported at the front and rear of the coach. On some MCI models, additional return porting is provided in the stepped aisleway at the front of the coach.

An innovative feature of the air distribution system being offered on the new MCI model 102A3 coach is the supply of recycled air through orificed directional nozzles located in the overhead baggage compartments. This system alters the air flow inside the bus (compared to older models), and it will likely become a standard feature on more buses in the near future.

These variations in bus air distribution systems suggest that the test program be conducted on more than one type or model of intercity coach. To take into account the variations between single and multi port exhausting and the introduction of recycled air above the window line on the air flow distribution, three different coaches should be tested. Suitable vehicles for the study would

be an MCI 102A3, an earlier MCI model, such as the MC9, and a Prévost Mirage or Marathon XL.

To ascertain the availability of suitable vehicles, a list of the coaches operated by Voyageur Colonial Limited was obtained. A summary of this list appears in Table 2.1. From this listing, it is evident that the representative test coaches to be used for this program are the MCI MC8 and Prévost Marathon XL. Although the testing of a 102A3 would have presented an interesting variation of the air flow distribution in intercity buses, the unavailability of a sample vehicle prevented any opportunity to conduct tests on a model with an overhead air system. Also, the project objective was to conduct air quality and distribution analysis on conventional intercity coaches. Although Voyageur Colonial operates more MC8 coaches than MC9, the air conditioning systems on these two models are virtually identical, and the latter model was chosen for the test program.

TABLE 2.1
Voyageur Fleet Distribution Summary (Ontario)

Models	Quantity
G.M.C.	15
MCI, MC7	22
MCI, MC8	67
MCI, MC9	36
Prévost, Marathon	1
Prévost, Marathon XL	10
Total	151

The test program concentrated on the MCI MC9 and Prévost Marathon XL coaches. To ensure that the results have wide applicability, part of the test program involved a comparison of coaches of the same model type. This permitted an evaluation of the variability in coach air conditioning system performance, since the degree of variability may have a significant influence on the test results.

2.3 Test Development

To obtain a preliminary assessment of the air flow within a typical coach interior, a series of flow visualization and measurement tests were conducted.

The preliminary flow visualization tests involved a comparison of air flow patterns inside the Prévost and MCI coaches for various test conditions. The test conditions included: stationary occupied and unoccupied coaches; unoccupied stationary and highway speed coaches; open driver's window at highway speeds; and operation of the driver's air conditioning system in unoccupied stationary and highway speed coaches. The preliminary flow measurement tests involved a comparison of the main air conditioning duct flow rates in three buses of the same model.

It was found that there were only minor differences in the general air flow patterns between (stationary) occupied and unoccupied coaches and between (unoccupied) stationary and highway speed coaches. At highway speeds the open driver's window caused a change in the air flow patterns in the immediate vicinity of the driver, but the influence did not extend into the passenger compartment. The driver's air conditioning system also affected the air flow characteristics in the immediate vicinity of the driver and this influence did extend into the forward portion of the passenger compartment. The effect of the driver's air conditioning system was similar for both the (unoccupied) stationary and highway speed tests. The preliminary flow visualization tests indicated that there were significant differences in the general air flow distribution patterns of the Prévost Marathon XL and MCI MC9 coaches due to the location of the ducting and return air

ports. The preliminary flow measurement tests indicated that differences in the order of 12% existed in the duct flow rates for the three sample MC9 coaches.

Since the preliminary results indicated that the physical characteristics and the operating conditions of the coach air conditioning systems were more significant than vehicle speed and degree of occupancy on the air flow distribution characteristics, the next phase of the test program was to obtain a detailed air flow analysis on both the Prévost and MCI coaches.

During the preliminary test work, the effect of varying the system controls and settings was investigated. Generally, where a particular setting had a significant effect on the air flow characteristics (such as the damper setting in the fresh air make-up duct), the test program included measurements over the full range of possible settings. In other cases, all tests were conducted with a given control setting. For example, on the MC9 coach, the door exhaust damper was left fully open and the driver's system fresh air make-up left fully closed, since these settings correspond to the normal coach operating conditions. The passenger air conditioning system was always set on high and the temperature setting was turned to minimum during cooling cycles and maximum during heating cycles. This resulted in a maximization of temperature differences and a subsequent minimization of temperature measurement errors. Similarly, the driver's system was operated on high with appropriate minimum or maximum temperature settings.

The development of the required qualitative and quantitative tests is described in detail in Section 2.3, pages 10 to 31 of the TES report included in Appendix A. The following is a summary of tests performed on both Prévost Marathon XL and MCI MC9 buses.

2.3.1 Volume Flow Rates

The flow rates of interest associated with the passenger compartment include:

- outdoor air intake
- exhaust fan
- conditioned air
- return air.

The air flow rates of the driver's ventilation system requiring measurement include:

- outdoor air intake
- conditioned air
- return air.

2.3.2 Air Speed and Direction

Local air velocities in the passenger compartment were obtained to determine whether air movement was adequate for passenger comfort. Air speed and direction measurements were taken at individual seat locations, at head and seat levels.

2.3.3 General Flow Patterns

Detailed air flow patterns were recorded graphically using smoke pencils at various cross sections within the test coaches. Air flow patterns were recorded for occupied and unoccupied coaches as well as stationary and highway speed coaches. Overall flow sketches were produced using smoke bombs to illustrate the relationship of the individual cross sectional flow sketches.

2.3.4 Ventilation System Balance

Volume flow rates were measured in the conditioned air ducts to show side to side balance. Integrated air speed measurements along each air diffuser were

taken to determine the front to back balance and to confirm the side to side balance.

Temperature measurements were recorded at flow measurement test points to confirm the findings of the other tests. For each air temperature test, the coach air conditioning system was operated in the cooling mode. By observing the consistency of the drop in air temperature along each diffuser, the ventilation system balance would be determined.

2.3.5 Outdoor Air Distribution

Qualitative test results were obtained by introducing smoke into the outdoor air intakes. The outdoor air distribution was observed by the outdoor air component traced with the smoke. The outdoor air distribution was observed at the diffuser outlets in the coach and the degree of mixing in the plenum was observed through the special plenum viewing doors.

The quantitative test involved using the air temperature measurements described previously. With the coach circulating fans operating normally, but with no heating or cooling in the plenum, an external heat source was applied at the outdoor air intakes. By measuring the temperature changes over time at the diffuser outlet, the outdoor air distribution was determined.

2.3.6 Particle Residence Time

The residence time of particles will be determined by monitoring the carbon dioxide concentrations in the conditioned air ducts. The fixed flow rate CO_2 source will be located in 3 consecutive positions; the front, middle and rear of test coaches.

For the MC9 when the source is located in the rear, two sets of tests will be performed. One as before in the conditioned air ducts and the other in the bus,

at the front. The reason for the additional measurement is to distinguish between the multiple returns present in the MC9.

For each coach, a graph of the carbon dioxide concentration versus time (for a fixed flow rate CO_2 source) was produced to illustrate particle residence times.

2.4 Test Results and Discussion

2.4.1 Volume Flow Rates

Results are summarized for this aspect of the measurement program for the MC9 coach in Table 2.2 and the Marathon XL coach in Table 2.3. More detailed measurement results can be found in Appendix A.

TABLE 2.2
Volume Flow Rate Summary - MCI, MC9

Volume flow measurement locations		Component volume flows (ft^3/min)	Percentage of the total volume flow (%)
Passenger Compartment			
1. Conditioned air ducts	(R)	1176	45.9
	(L)	1388	54.1
		2564	100.0
2. Fresh air intakes			
(i) Open		206	8.0
(ii) Closed		33.0	1.3
3. Exhaust vents		86.9	3.4
4. Leakage			4.6
5. Recycled vents			
(i) rear side		431	16.8
(ii) front side		309	12.1
(iii) front aisle		1516	59.1
		2256	88.0

TABLE 2.3
Volume Flow Rate Summary - Prévost, Marathon XL

	Volume flow measurement locations		Component volume flows (ft^3/min)	Percentage of the total volume flow (%)
Passenger Compartment				
1.	Conditioned air ducts	(R)	1506	59.1
		(L)	1041	40.9
			2547	100.0
2.	Fresh air intakes			
	(i) Full closed		201.9	
	(ii) Middle		219.3	8.6
	(iii) Full Open		230.9	
3.	Washroom exhaust		68.8	2.7
4.	Leakage			5.9
5.	Recycled air		2221	87.2

The total flow in the conditioned air ducts is almost identical for the two coaches, 2564 cfm and 2547 cfm for the MC9 and Marathon XL, respectively. In the MC9, the flow feeding the right hand side (RHS) of the coach was 1176 cfm and the flow feeding the left hand side (LHS) was 1388 cfm, a difference of about 17%. In the Marathon XL, the RHS flow was 1506 cfm and the LHS flow was 1041 cfm, a difference of about 37%. Although the measured total conditioned air flows were close to the manufacturer's specifications for both coaches, it is apparent that the duct flow balance could be improved.

For both test coaches, the fresh air intake flows were measured at both extremes of damper adjustment. For the MC9, the total fresh air intake flow was 33 cfm with the dampers in the closed position and 206 cfm with the dampers in the open position. These values represent 1.3% and 8.0% of the total conditioned

air flow, respectively. For the Marathon XL, the fresh air intake flow varied from 201.9 cfm with the damper in position "one" (minimum flow), to 219.3 cfm with the damper in position "three" to 230.9 cfm with the damper in position "five" (maximum flow). These values represent 7.9%, 8.6% and 9.1% of the total conditioned air flow, respectively. It is apparent that the coach fresh air intake is always below 10% of the conditioned air flow, which is much lower than the 20% figure specified by the coach manufacturers. With maximum ventilation rates, the fresh air supply is in the range of 5 cfm per seat. This ventilation rate is less than half of the commonly accepted standard of 15 cfm per person for building environments.

It is very likely that the low fresh air flow rates are a key reason for passenger complaints about poor air quality. This is particularly true for the MC9 coach, which is normally operated with the fresh air dampers fully closed (i.e., fresh air intake of only 1.3% of the conditioned air flow).

The exhaust air flow rates measured for the two coaches were 86.9 cfm for the MC9 (door vent and washroom exhaust), and 68.8 cfm for the Marathon XL (washroom exhaust only). These figures represent 3.4% and 2.7% of the conditioned air flows, respectively. Since the air conditioning systems must be in a state of equilibrium, the exhaust flow rates must equal their respective intake flow rates. For the MC9 coach, the intake flow was 119.1 cfm (4.6% of the conditioned air flow) higher than the exhaust flow rate. For the Marathon XL, the intake flow was 150.5 cfm (5.9% of the conditioned air flow) higher than the exhaust flow rate. These differences are attributable to leakage.

Air flow measurements were taken in the passenger compartments of the coaches to provide an indication of the air conditioning system return air flow rates. For the MC9, the return air flow rate was 2256 cfm (88% of the conditioned air flow rate) and for the Marathon XL, the return air flow rate was 2221 cfm (87.2% of the conditioned air flow rate). Theoretically, the fresh air intake flow plus the return air flow equals the conditioned air flow. Any discrepancies in this identity are due to either air leakage or measurement errors. The air flow measurement

errors were minimized by using highly accurate and properly ranged and calibrated instrumentation. For the MC9, the sum of the intake and return air flows was 2462 cfm, or 96% of the conditioned air flow. For the Marathon XL, the sum of the intake and return air flows was 2452 cfm, or 96% of the conditioned air flow. Therefore, the 4% discrepancy is largely attributed to the leakage in the return air system. In the MC9, this leakage flow enters the plenum from the forward baggage compartment and in the Marathon XL, this leakage flow enters the plenum from outside the coach.

The return air vents on the MC9 exhibited unbalanced flow, as shown in Table 2.2. The return air vents on either side of the front aisle carry two thirds of the return air flow, with the remaining third being divided between the front and rear side wall return ports.

Detailed air flow measurements for the driver's air conditioning system for both coaches are contained in Appendix A, Tables A2 and B2. Although the driver's air conditioning systems do not have a significant impact on the air quality of the coaches, flow measurements for the driver's systems are included for completeness.

As described previously in the report, preliminary testing indicated that only minor differences in the coach air flow characteristics resulted from highway versus stationary measurements. As shown in Appendix A, Tables A2 and B2, sample measurements taken at highway speeds do not generally show significant differences from stationary measurements. However, one flow increment worth noting is the door exhaust on the MC9. The door exhaust flow rate increased from 40.8 cfm (with the coach stationary) to 106.6 cfm (with the coach travelling at 90 km/h). This flow increase is due to the reduced pressure at this point on the coach exterior caused by driving. Although the increase in the door exhaust flow rate is somewhat dependent on wind conditions, it should be noted that the increase of 65.8 cfm is only 2.6% of the total conditioned air flow and hence is not considered to be significant.

2.4.2 Air Speed and Direction

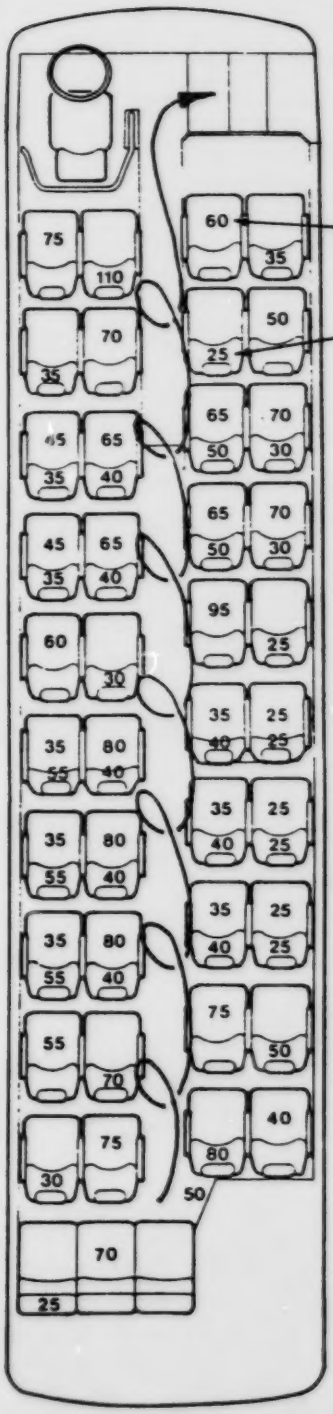
To determine whether the air speeds in the passenger compartment were within a reasonable comfort range, a number of air speed measurements were taken at passenger head and seat levels. To ensure that the flow measurement instrument was properly oriented during each measurement, smoke pencils were used to determine the air flow direction. The discreet air speed measurements obtained are shown in the sketches of Figures 2.1 and 2.2 for the MC9 and Marathon XL, respectively.

The generally accepted standard for a maximum comfortable air speed in general ventilation systems is 50 fpm. It can be seen from the specified figures that some of the local air speeds in both coaches exceed this standard by a large margin. Thus, air speed may be a contributing factor to the passenger air quality complaints being received by coach operators. There are no readings below 20 fpm. This minimum level is sufficient to ensure good mixing action and eliminate stagnant pockets of air.

Figure 2.1 shows the overall flow pattern inside the MC9 coach with the coach stationary and the driver's air conditioning system turned off. Although conditioned air enters the passenger compartment evenly through the diffusers along the window line, there is a strong forward flow tendency in the coach. This forward flow is caused by the strong pull of the front aisle return ports (through which two thirds of the return air flows), and by the flow leaving the coach through the door exhaust port. The forward flow in the coach is spiral in nature due to the vorticular flow caused by the conditioned air exiting the diffusers and by the staggered seat positioning. The numbers which appear in Figure 2.1 identify the local head and seat level air velocities in fpm.

FIGURE 2.1

**Overall Flow Sketch (Stationary Coach)
and Discreet Air Speed Measurements
MCI, MC9**



TYPICAL READING AT SEAT LEVEL

TYPICAL READING AT HEAD LEVEL

Average Air Velocities (fpm)

	Left	Right
Head Level	25.6	38.7
Seat Level	60.6	51.3
Overall	43.1	44.8

Figure 2.2 shows the overall flow pattern in the Marathon XL coach under stationary conditions with the driver's system off. Since this coach utilizes a single return air port under the left hand seats (see Figure 2.2), the general flow is from the front and rear of the coach towards the centre. At the very front of the coach, there is a forward flow tendency in the upper portion of the passenger compartment and a rearward flow tendency in the lower portion of the passenger compartment. Also, in the first row of right hand seats, there is a flow tendency from the diffuser to the driver's window. This flow was very pronounced when the driver's window was open, but it also existed when the window was closed, indicating that some leakage occurred around the window seal. The numbers which appear in Figure 2.2 identify the local head and seat level air velocities in fpm.

2.4.3 General Flow Patterns

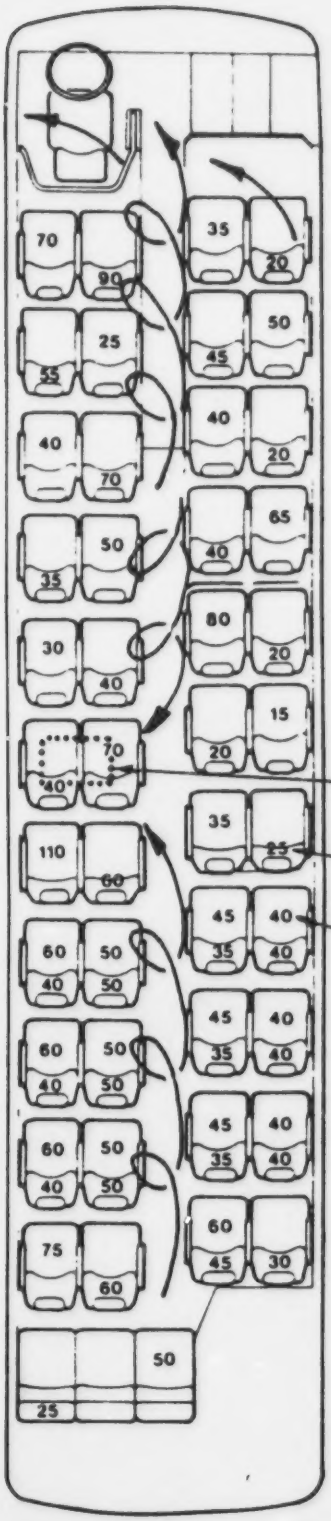
Overall flow patterns were sketched for each coach and sketches were also produced at each seat cross section. Sketches are contained in the TES report in Appendix A. The flow sketches provide a comprehensive representation of the general flow patterns inside each coach and illustrate the effects on air flow patterns by factors such as passenger occupancy, coach speed and driver's air conditioning system operation.

2.4.3.1 MC9 Coach

With the driver's system on in the MC9 coach, there is substantial turbulence in the first row of seats, but only a minimal effect is apparent in the second row. The air flow pattern at all other seats is not affected by the operation of the driver's air conditioning system.

FIGURE 2.2

**Overall Flow Sketch (Stationary Coach)
and Discreet Air Speed Measurements
Prevost, Marathon XL**



OUTLINE OF RETURN AIR PORT

TYPICAL READING AT HEAD LEVEL

TYPICAL READING AT SEAT LEVEL

Average Air Velocities (fpm)

	Left	Right
Head Level	49.7	32.7
Seat Level	56.7	46.4
Overall	53.2	39.3

With the driver's window closed, the coach interior air flow pattern at highway speed is identical to the stationary overall flow pattern. When the driver's window is open, air from inside the coach is drawn out through the window past the driver. This flow does not affect the air flow patterns in any of the passenger seats.

The general air flow patterns in the coach were not altered significantly by the presence of passengers. However, one minor difference was noted. Under unoccupied conditions there was a tendency for air to move forward under the passenger seats. Under occupied conditions, this tendency was reduced due to the resistance caused by the passengers' legs.

2.4.3.2 Marathon XL Coach

An analysis of flow patterns indicated that the flow in the front portion of the Marathon XL coach is not symmetrical, due to a strong flow from the right side diffuser impinging on the left side of the coach. The reason for the non-symmetrical flow in this coach is the unbalanced right to left air distribution exiting the diffusers. Another consequence of the uneven flow distribution is an increase in turbulence (flow instability).

The comparison of flow sketches for the Marathon XL travelling at highway speed (90 km/hr) with flow sketches of a stationary coach shows that there is virtually no difference in the air flow patterns between stationary and highway speed conditions.

Additional tests conducted on the Marathon XL indicate that the effect of passenger occupancy on the coach air flow characteristics was minimal. As noted for the MC9 coach, the only effect of passenger occupancy was a slight reduction in the air flow along the floor under the passenger seats. Tests were also conducted to determine the effect of the driver's air conditioning system on the passenger compartment air flow characteristics. The turbulence in the front of the coach caused by the unbalanced diffuser flows tended to mask the effects of

the driver's air conditioning system, and consequently, there were no discernible differences in the passenger compartment air flow patterns with the driver's system on or off.

To summarize the overall air flow patterns in the two coaches, three dimensional flow sketches were produced. These sketches are shown in Figures 2.3 and 2.4 for the MC9 and Marathon XL, respectively.

2.4.4 Ventilation System Balance

The overall ventilation system balance can be an important factor in passenger comfort, since it determines the distribution of conditioned air to the passengers. The general left to right balance of the coach air conditioning systems can be determined by measuring the conditioned air flows in the main ducts. As noted previously, the flows in the conditioned air ducts of the MC9 coach were 1176 cfm to the right and 1388 cfm to the left, a difference of about 17%. For the Marathon XL coach, the flows were 1506 cfm to the right and 1041 cfm to the left, a difference of about 37%. While these figures provide a general indication of the left to right conditioned air balance, they do not provide any detailed information on the conditioned air distribution in the passenger compartment.

To determine the distribution of conditioned air entering the coach passenger compartments, velocity profiles at the diffuser outlets were constructed for each coach. Two velocity profiles for each side of each coach were produced, one profile for each of two elevations above the diffuser. These profiles are shown in Figures 2.5 and 2.6 for the MC9 coach and in Figures 2.7 and 2.8 for the Marathon XL coach. From these figures, it is apparent that there is a considerable amount of scatter in the data. This scatter is a consequence of the diffuser design. The diffuser consists of a series of square orifices such that the

FIGURE 2.3

Overall Flow Sketch - MC9

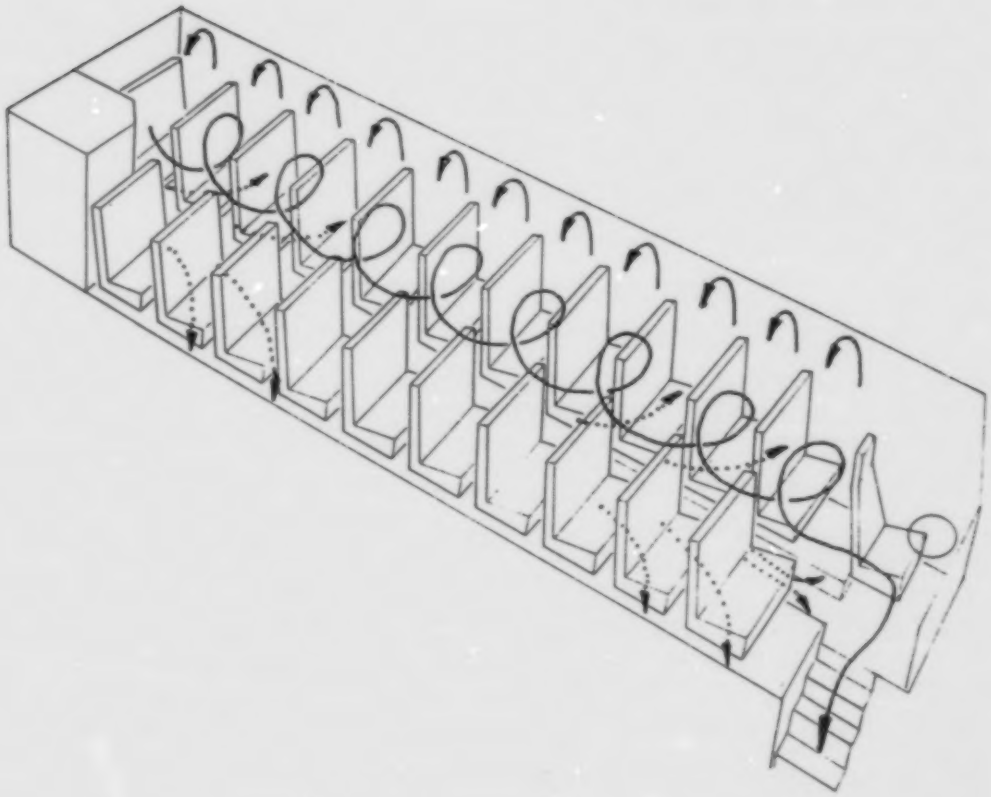
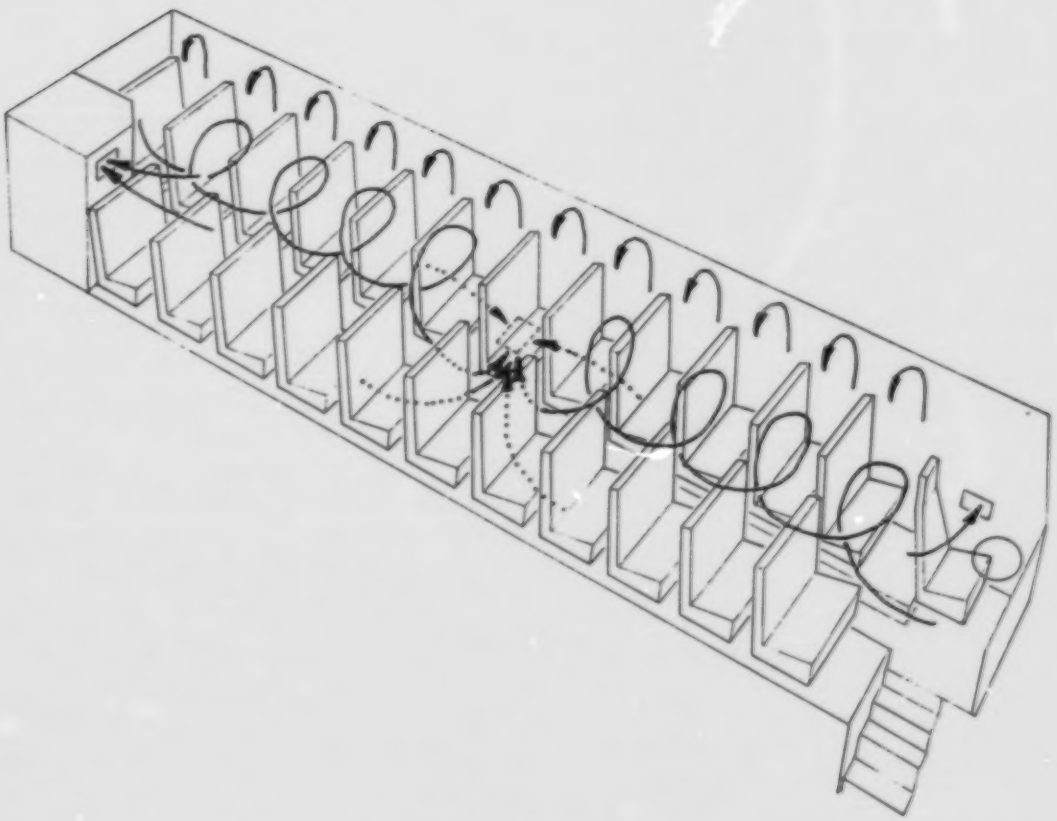


FIGURE 2.4

Overall Flow Sketch - Marathon XL



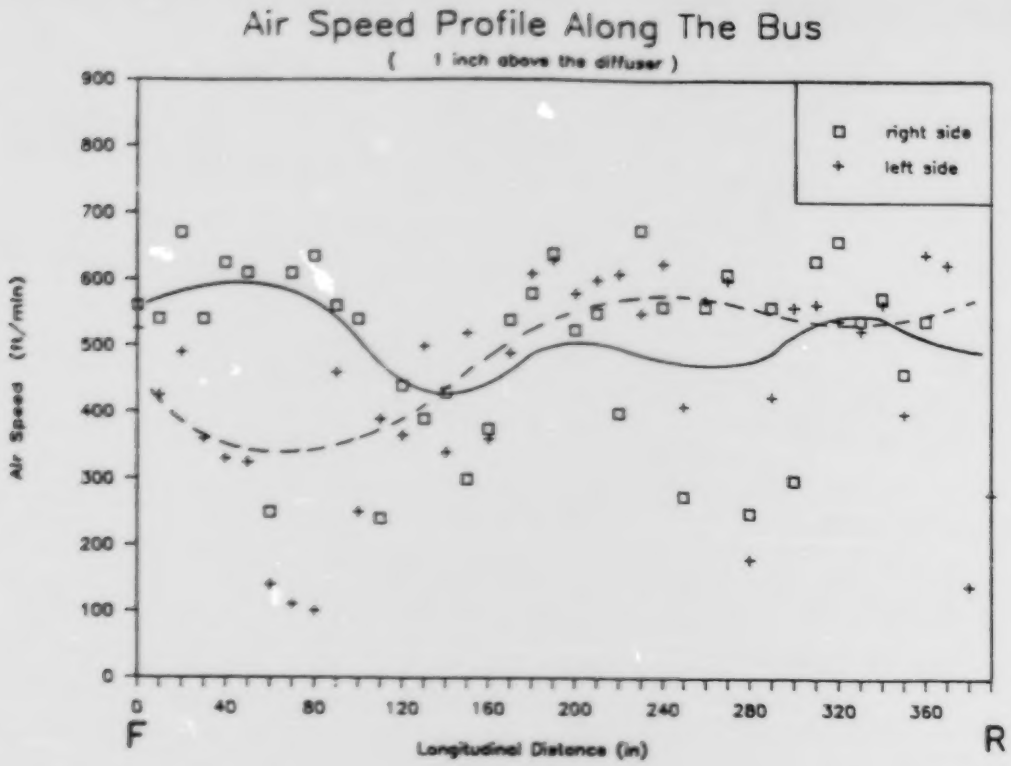


FIGURE 2.5

Air Speed Profiles (1 Inch Above Diffuser)
MC9

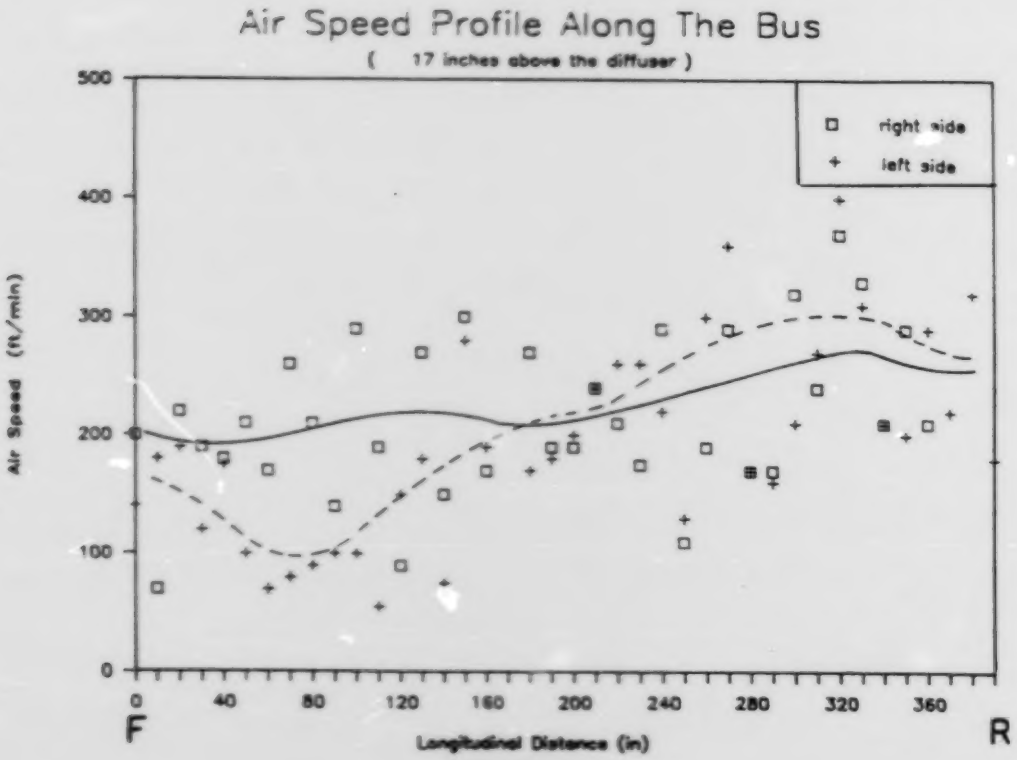


FIGURE 2.6

Air Speed Profiles (17 Inches Above Diffuser)
MC9

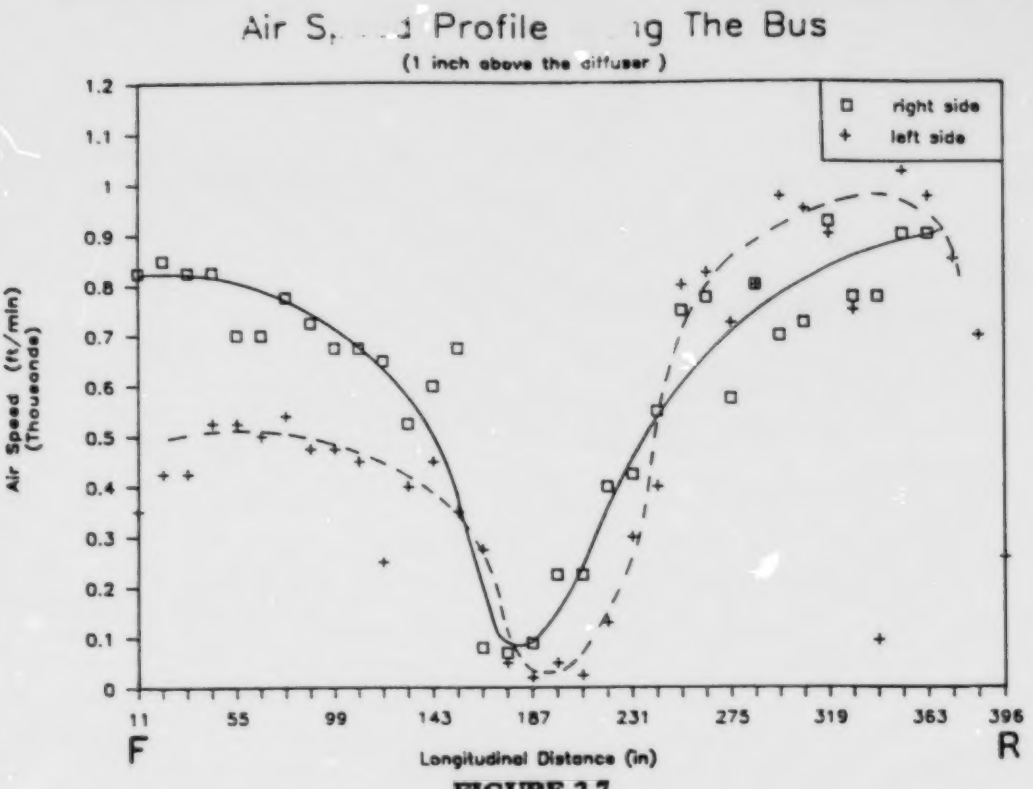


FIGURE 2.7

Air Speed Profiles (1 Inch Above Diffuser)
Marathon XL

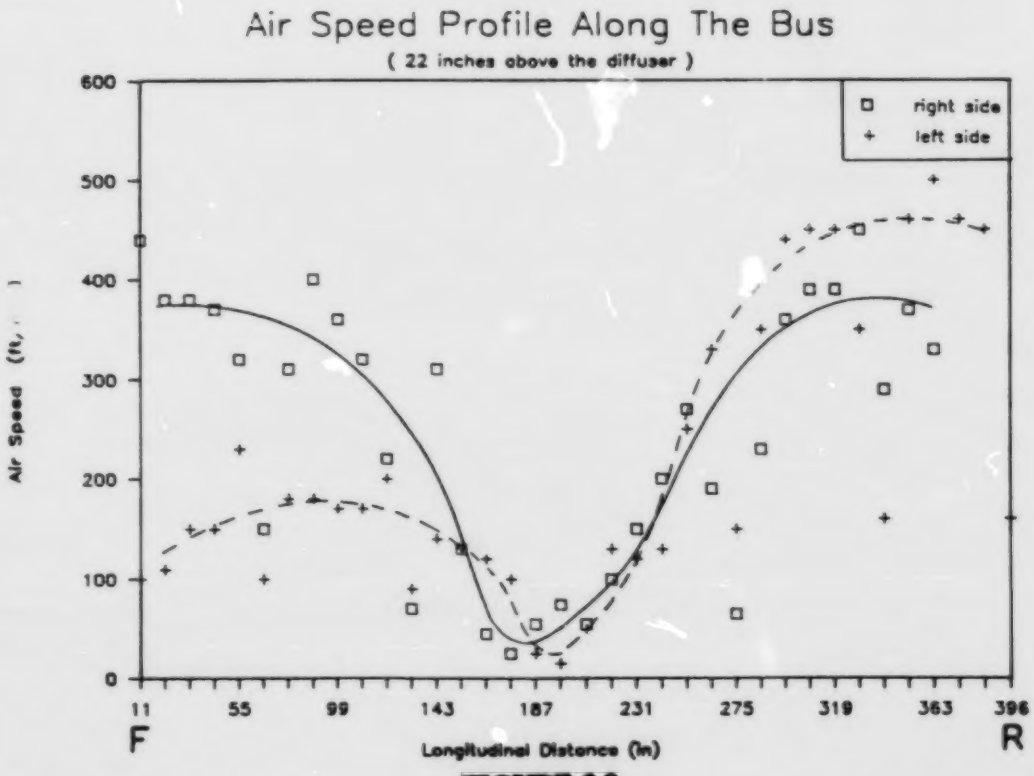


FIGURE 2.8

Air Speed Profiles (22 Inches Above Diffuser)
Marathon XL

air flow along the diffuser is not continuous. Consequently, the profiles in Figures 2.5, 2.6, 2.7 and 2.8 should be used only as an approximate indicator of the longitudinal air flow distribution.

Figures 2.5 and 2.6 show that the conditioned air distribution on the MC9 is relatively uniform, both laterally and longitudinally. For the Marathon XL, however, the conditioned air distribution is very non-uniform, as shown in Figures 2.7 and 2.8. In this case, there is much higher flow at the front and rear of the coach, relative to the centre, as well as a considerable difference in the left to right flow balance. The uneven longitudinal air distribution reduces flow short circuiting because of the control location of the return air port.

A modification kit is available from Prévost which can be used to increase the air flow to the centre portion of the coach. The kit consists of a number of deflectors which are installed on each side of the coach to provide more uniform longitudinal air distribution (it should be noted that this modification will not affect the left to right flow balance in the coach). Details concerning the available modification kit are contained in the TES report in Appendix A.

Smoke bomb tests were conducted to provide additional qualitative information on the conditioned air distribution. Smoke introduced into each coach plenum via the fresh air intakes provided a method of visibly observing the conditioned air distribution in the passenger compartment. These tests showed a relatively even distribution on the MC9, while on the Marathon XL there was a definite right side flow bias with heavier front and rear smoke concentrations. Thus, the results of the smoke tests are in agreement with the measured velocity profiles.

Temperature tests were conducted to evaluate temperature uniformity at the diffuser outlets. For these tests, the passenger air conditioning systems were operated in the cooling mode for a period of ten minutes, with temperature profiles being automatically monitored every ten seconds. Temperature profiles were plotted for each side of each coach at times of zero, one, two, five and ten minutes into the test. For the MC9 coach, the right and left temperature profiles

are shown in Figures 2.9 and 2.10. For the Marathon XL, the right and left temperature profiles are shown in Figures 2.11 and 2.12.

As shown in Figures 2.9 and 2.10, the temperature profiles for the MC9 are very uniform during the cooling cycle. This indicates that full mixing of the cooled air is occurring in the plenum and that this air is being evenly distributed in the passenger compartment. As shown in Figures 2.11 and 2.12, the temperature profiles for the Marathon XL are not completely uniform. At the end of the cooling cycle, the air temperature in the central part of the coach is higher than the air temperatures in the front and rear. These temperature profiles are a direct consequence of the air velocity profiles (as shown in Figures 2.7 and 2.8).

2.4.5 Fresh Air Distribution

The previous section described the conditioned air distribution in the test coaches. In addition to knowing the conditioned air distribution, it is important to know how the fresh air component of the conditioned air is distributed. This can be determined relatively easily by establishing the degree of fresh air mixing in the air conditioning system plenum.

During the smoke bomb tests, smoke was introduced into the air conditioning plenum through the fresh air intake ducts. Thus, the smoke represented the fresh air component of the conditioned air. During each test, the smoke concentration was observed in the passenger compartment and in the plenum (through the acrylic viewing door).

For the MC9 coach, three smoke bomb tests were conducted. These tests involved introducing smoke into the left and right fresh air intakes both separately and simultaneously. The results of the three tests were identical in that full mixing occurred in the plenum and smoke concentrations in the

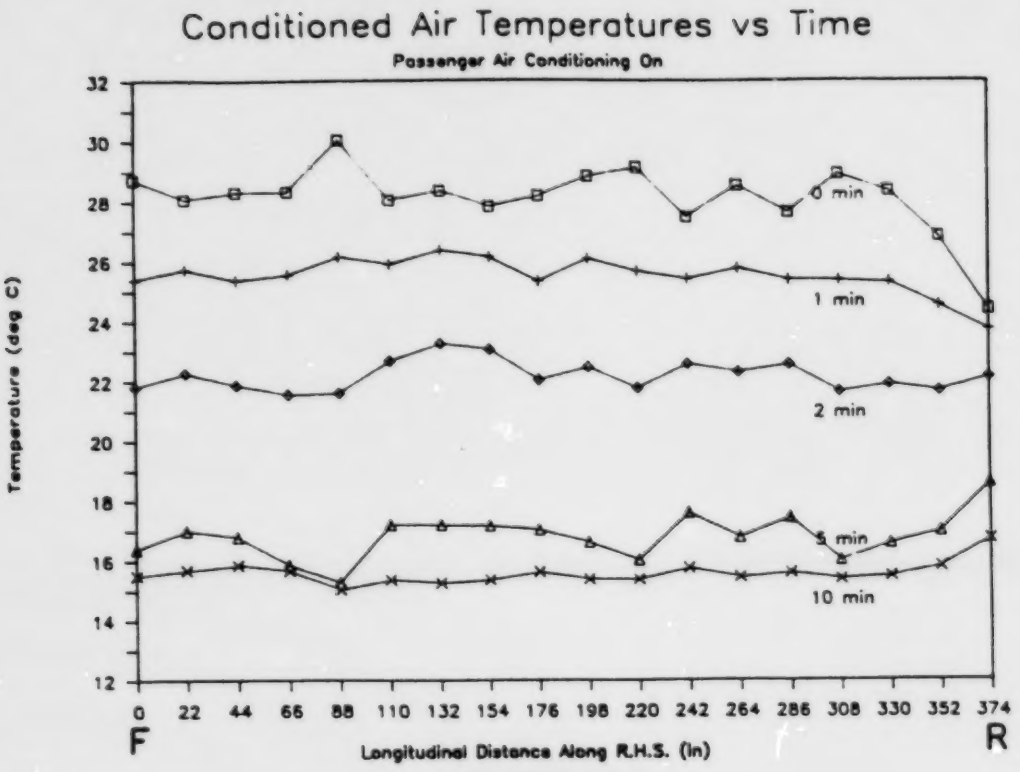


FIGURE 2.9

MC9 Coach RHS Temperature Profiles (Cooling Mode)

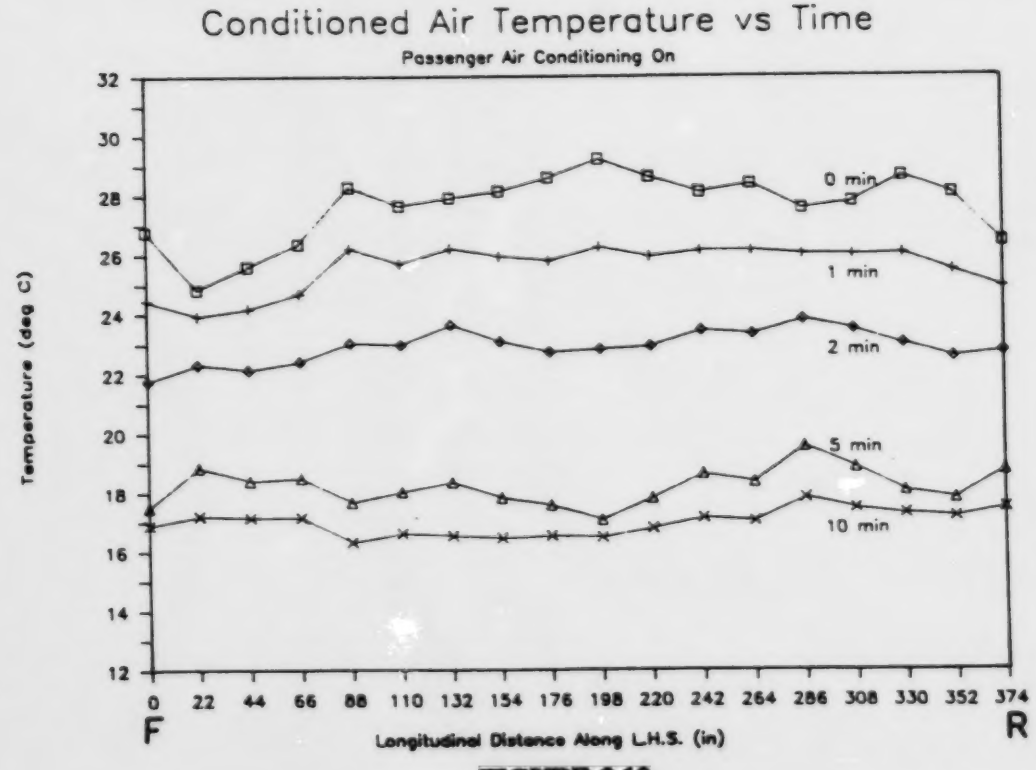


FIGURE 2.10

MC9 Coach LHS Temperature Profiles (Cooling Mode)

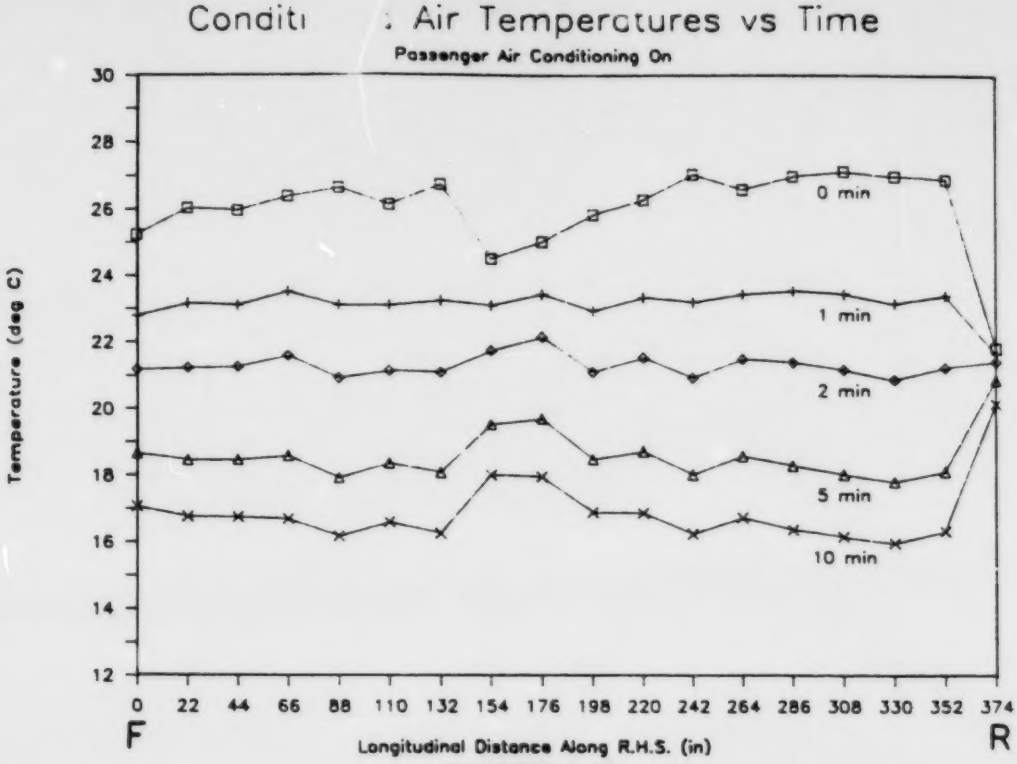


FIGURE 2.11

Marathon XL Coach RHS Temperature Profiles (Cooling Mode)

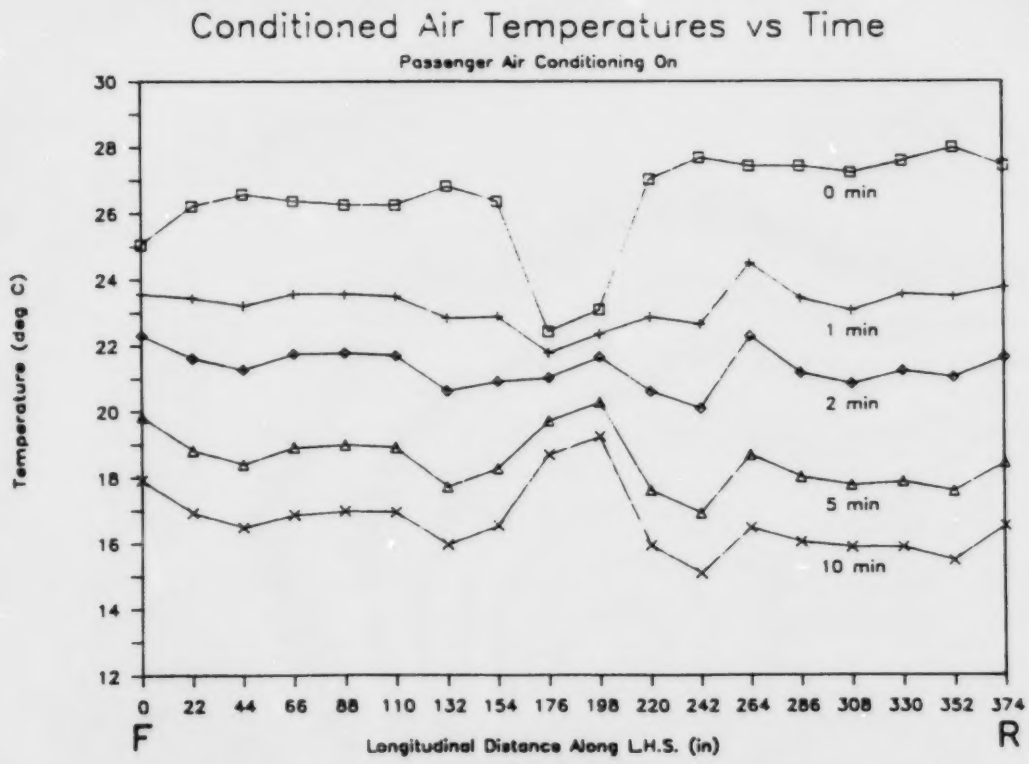


FIGURE 2.12

Marathon XL Coach LHS Temperature Profiles (Cooling Mode)

passenger compartment were correspondingly uniform. Thus, with full mixing in the plenum, the fresh air distribution in the passenger compartment is identical to the conditioned air distribution, which is relatively uniform in the MC9 coach.

For the Marathon XL coach, a single smoke bomb test was conducted since this coach utilizes a single fresh air intake port. The smoke mixed fully in the plenum, such that the fresh air component was evenly distributed in the conditioned air. Thus, the fresh air distribution in the passenger compartment is identical to the conditioned air distribution, which is non-uniform in the Marathon XL coach. This was confirmed by observing the smoke concentrations in the passenger compartment which closely paralleled the measured velocity profiles.

To quantify the smoke test results, temperature tests were conducted using the thermocouple arrangement previously described. With an external heat source applied at the fresh air intake, the fresh air component of the conditioned air was at a much higher temperature than the return air component. Thus, by measuring air temperatures at the diffuser outlet, the fresh air distribution in the passenger compartment was determined. As with the smoke tests, three temperature tests were conducted on the MC9 and one temperature test was conducted on the Marathon XL. During each test, temperature profiles were measured over a period of ten minutes.

Figures 2.13 and 2.14 show temperature profiles for the right and left sides of the MC9 coach, with the heat source being applied at the left side fresh air intake. From Figure 2.13, it can be seen that the right side temperature profiles show a consistent temperature increase, with the individual temperature profiles being very uniform (with the exception of the thermocouple located in the washroom). On the left side, as shown in Figure 2.14, the temperature profiles show a consistent temperature increase, but the individual temperature profiles are not as uniform as those on the right side. The reason for the higher temperatures at

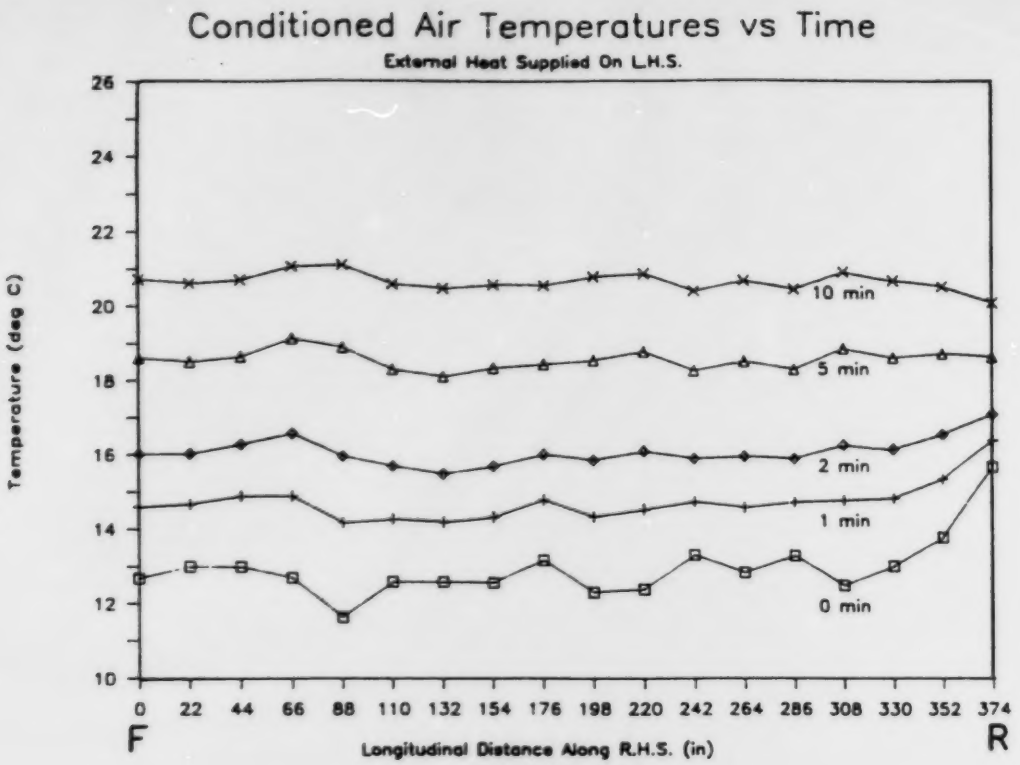


FIGURE 2.13

MC9 Coach RHS Temperature Profiles - External Heat Source Applied to Preheat Supply of Fresh Air to Verify Distribution

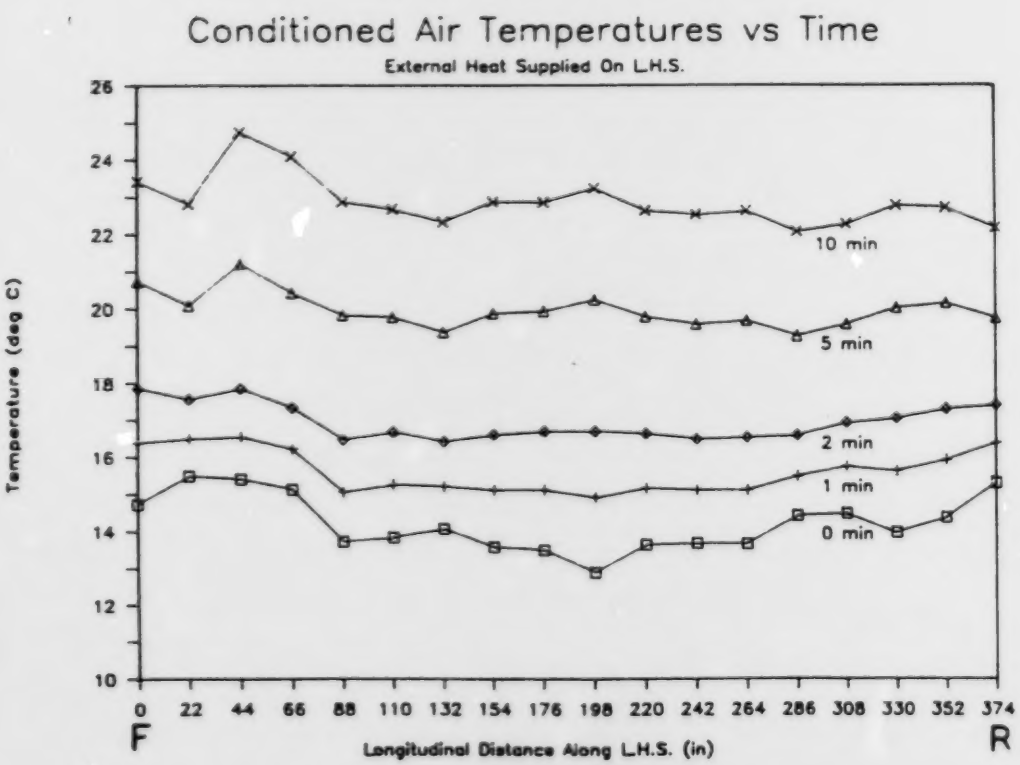


FIGURE 2.14

MC9 Coach LHS Temperature Profiles - External Heat Source Applied to Preheat Supply of Fresh Air to Verify Distribution

a longitudinal distance of 44 inches on the left side, is that conduction and convection cause a local temperature increase at the point of application of the heat source (the fresh air intake ports on the MC9 are located just below the window line). Thus, the temperature measurements confirm that the fresh air component of the conditioned air is distributed evenly in the MC9 coach. The remaining two temperature tests (with the heat source located at the right side fresh air intake and with a heat source located at both of the fresh air intakes), provided the same results as the first test. In both cases, the temperature profiles showed consistent increases and the individual temperature profiles were quite uniform with the exception of localized temperature increases at the point (or points) of heat application.

Figures 2.15 and 2.16 show temperature profiles for the right and left sides of the Marathon XL coach, with the heat source being applied at the single left side fresh air intake. It can be seen from these figures that the heating profiles closely parallel the measured velocity profiles. The overall temperature rise on the right side of the coach was substantially higher than on the left side, due to the higher right side conditioned air flow. Similarly, on both the right and left sides of the coach, the temperature rise in the central section of the coach is lower than in the front and rear sections due to the reduced conditioned air flows in the centre. The temperature profiles shown in Figures 2.15 and 2.16 show that the fresh air distribution is the same as the conditioned air distribution, indicating that full mixing of fresh air and return air occurs in the plenum.

2.4.6 Particle Residence Times

To determine particle residence times, carbon dioxide tracer gas tests were conducted. For each of the tests (four on the MC9 coach and three on the Marathon XL coach), the carbon dioxide source was set at 35 standard cubic feet per hour.

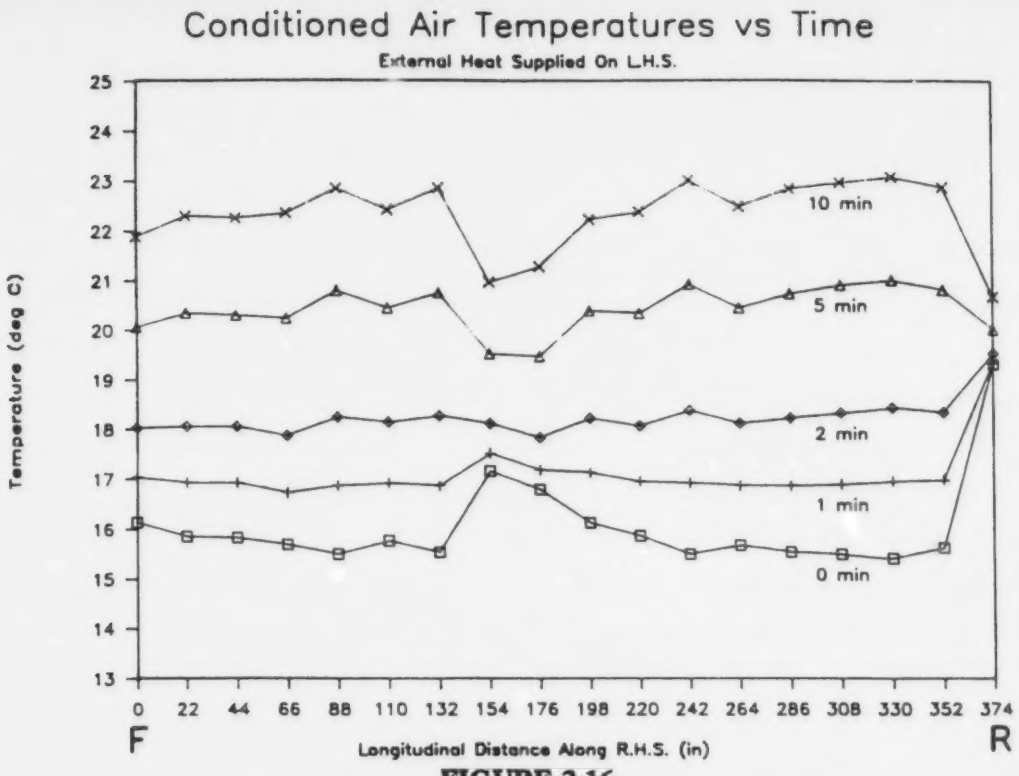


FIGURE 2.16

Marathon XL Coach RHS Temperature Profiles - External Heat Source Applied to Preheat Supply of Fresh Air to Verify Distribution

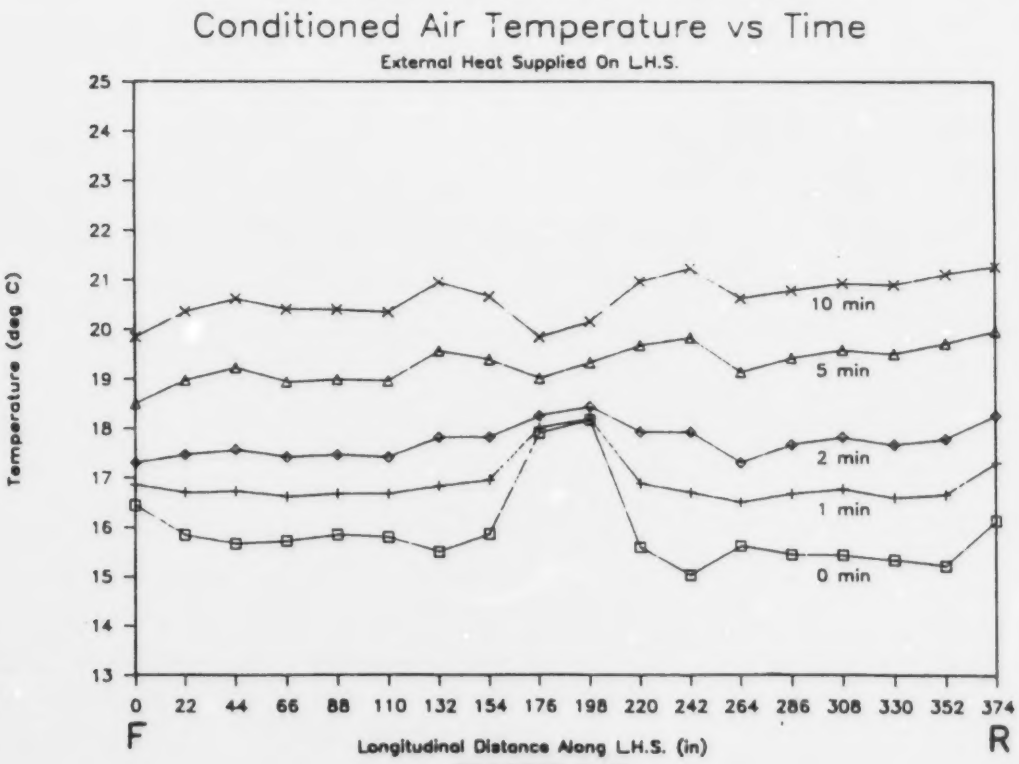


FIGURE 2.15

Marathon XL Coach LHS Temperature Profiles - External Heat Source Applied to Preheat Supply of Fresh Air to Verify Distribution

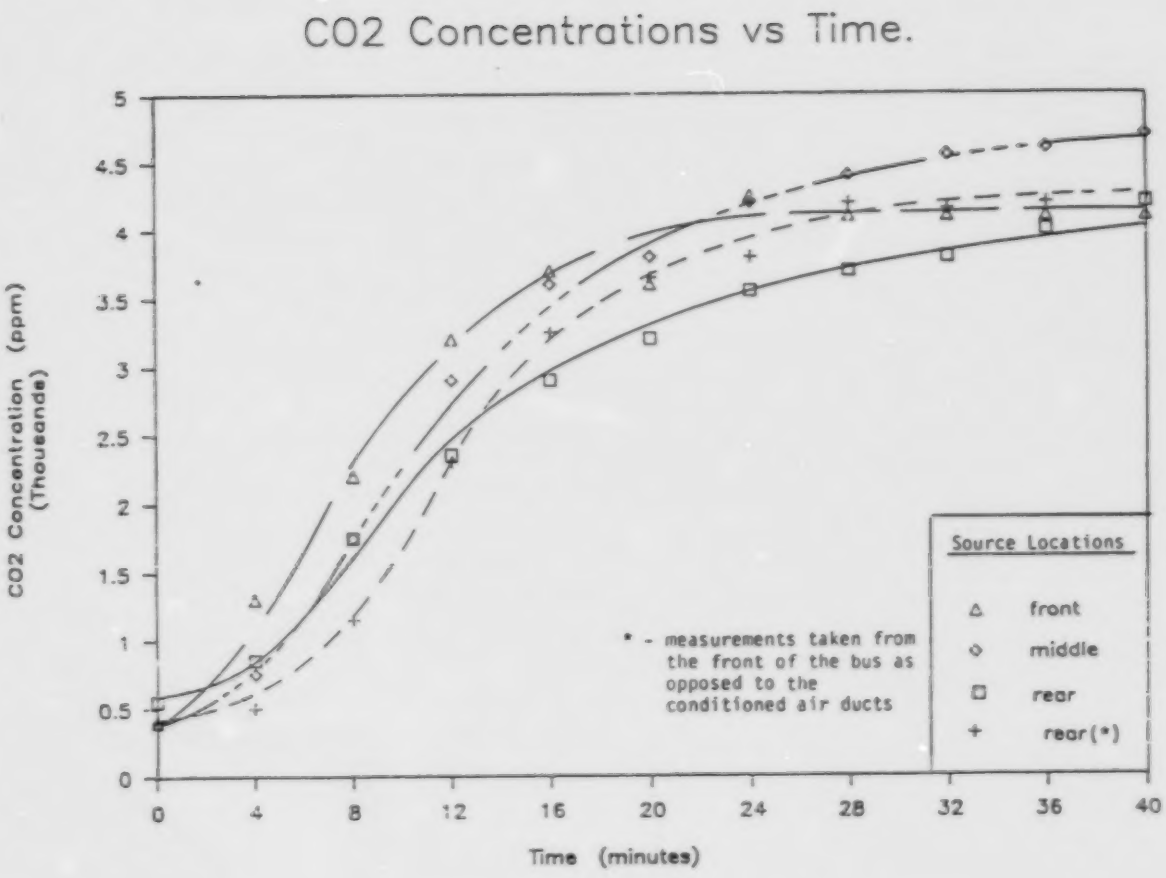
For the MC9 coach, three of the tests involved measuring the carbon dioxide concentrations in the conditioned air ducts with the source located at the front, middle and rear of the coach passenger compartment. An additional test was conducted with the carbon dioxide concentration being measured at the front of the passenger compartment while the source was located in the rear of the coach. The results of the four tests are shown in Figure 2.17. It can be seen from this figure that the carbon dioxide concentration in the conditioned air increased most rapidly with the source located in the front of the coach. This is due to the strong pull of the front return air ports. With the source located in the middle of the coach, the measured carbon dioxide concentration experienced a time lag (of about two minutes), since the tracer gas had to travel from the middle of the coach to the front return air ports.

With the source located in the rear of the coach, the carbon dioxide concentration is initially higher than for the centre position, with a cross over occurring at a time of about six minutes. The initial higher concentration is due to carbon dioxide entering the rear return air ports and getting into the air conditioning system quite quickly. However, most of the tracer gas travels through the entire coach and enters the air conditioning system via the front return ports. Since most of the gas must travel through the entire coach, this source location provides the longest time lag of the three positions.

With the source located at the rear of the coach and with the carbon dioxide concentration measurements being taken at the front of the coach, the greatest time lag was observed (about four minutes difference compared with the source located at the front). This provides an indication of the time required for the tracer gas to travel the length of the coach, since the tracer gas entering the rear return ports is not measured.

FIGURE 2.17

MC9 - Carbon Dioxide Concentrations Versus Time



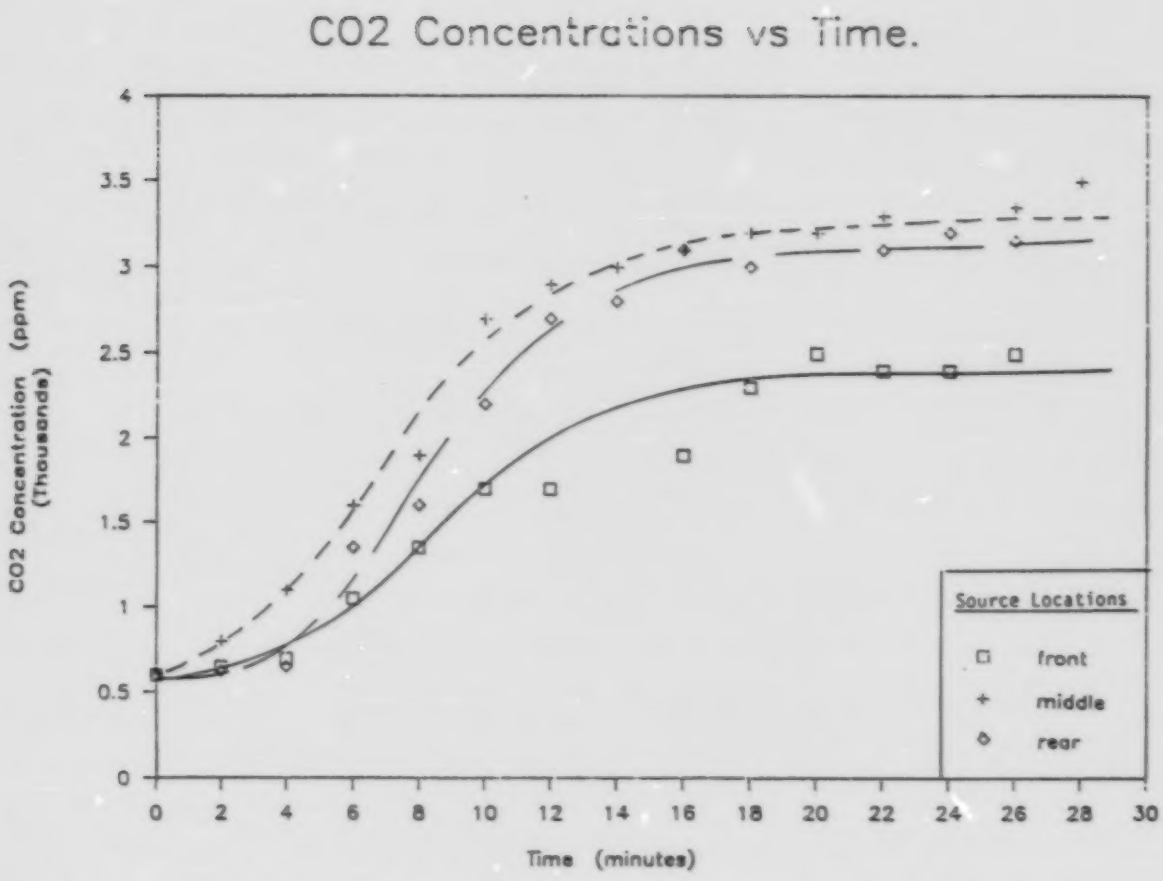
The results of the four tests indicate that for a pollutant source located anywhere in the coach, most or all of the pollutant would travel through the coach to the front return air ports. Once the pollutant enters the air conditioning system, it is distributed throughout the coach. For any pollutant source location, a steady state situation is reached after about 25 minutes, with time lags of up to four minutes caused by varying the source location. This suggests that cigarette smoking passengers should be located in the front of the coach, provided that the cigarette smoke can be filtered out of the return air or conditioned air before it is returned to the passenger compartment.

For the Marathon XL coach, the carbon dioxide concentration was measured in the conditioned air ducts with the carbon dioxide source located at the front, middle and rear of the coach passenger compartment. The results of the three tests are shown in Figure 2.18. The fastest rise in tracer gas concentration occurred for the source located in the centre of the coach, since this is where the single return air port is located. With the source located in the rear of the coach, a time lag of between one and two minutes occurred, due to the tracer gas travelling from the rear of the coach to the central return air port. For the test with the source located in the front of the coach, a problem was encountered with the carbon dioxide regulator. After setting the source at 35 standard cubic feet per hour, freezing of the regulator a few minutes into the test caused the flow to drop and consequently, the steady state gas concentration for this test was lower than for the other two tests. However, in the initial part of the test, the measured concentrations were almost identical to the values measured for the source in the rear location. This indicates that the time lag is the same for the front and rear source locations, which is as expected, since the return air port is located in the centre of the coach.

The results of the three tests indicate that for a pollutant source located anywhere in the coach, all of the pollutant would travel to the central return air port. Once the pollutant enters the air conditioning system, it is distributed

FIGURE 2.18

Marathon XL - Carbon Dioxide Concentrations Versus Time



throughout the coach. For any pollutant source location, it is distributed throughout the coach. For any pollutant source location, a steady state situation is reached after about 16 minutes, with a time lag of between one and two minutes caused by varying the source location. This suggests that cigarette smoking passengers should be located in the centre of the coach, provided that the cigarette smoke can be filtered out of the return air or conditioned air before it is returned to the passenger compartment.

3.0 SMOKE CONCENTRATIONS AT SOURCE AND IN RECIRCULATED AIR

Tobacco smoking results in the emission of respirable particles (average diameters in the range of 0.1 to 0.5 microns), as well as gases and trace metals. For each cigarette burned, billions of particles are emitted resulting in approximately 11 milligrams (mg) of total airborne particulate mass. About 1000 different polynuclear aromatic hydrocarbons (PAH's), many of significant concern to human health, are associated with the particulate phase.

However, air sampling and analytical methods for PAH's are difficult and expensive. Therefore, cigarette smoke concentrations are more frequently monitored by determining concentrations of airborne respirable particulate.

The objective of this task was to determine air concentrations of cigarette smoke near the source, in the supply air, and in the exhaust air. Measurements were made in one model each of MCI and Prévost buses, under partially controlled conditions:

(i) vehicle operating conditions were "normal" (i.e. fresh air intake in MCI effectively closed, on Prévost as received);

(ii) vehicle was empty, except for smoker (source) and observer making measurements; and

(iii) individually controlled passenger air jets were turned off.

However, no attempt was made to standardize the way each cigarette was held or smoked. The measurement methods and results are described in the following section.

3.1 Measurement Methods for Respirable Particulate

Real time analyses of airborne respirable particulate concentrations were done using a Sibata digital dust indicator (Model P-5). The instrument determines relative concentrations of airborne particulate by measuring the intensity of light scattered by particulate passing through an illumination chamber. The instrument is factory-calibrated with an aerosol of stearic acid (median aerodynamic diameter 0.3 micron). This means it is most accurate with airborne particles in this size range. The instrument readout is in counts per minute (cpm), which is roughly equivalent to micrograms per cubic meter ($\mu g/m^3$) for particulate with similar size distribution. As cigarette smoke particle size distribution is in this range, the instrument readout in cpm can be roughly equated to $\mu g/m^3$.

One minute measurements were made sequentially in the following locations around the smoke source:

1. Adjacent seat.
2. Seat in front, at window.
3. Seat in front, at aisle.
4. Seat behind, at window.
5. Seat behind, at aisle.
6. Adjacent seat (repeated).

If smoke source (smoker) was sitting in an aisle seat, then additional measurements were made in the:

7. Seat across aisle.
8. Seat across aisle and in front.
9. Seat across aisle and in back.

One minute measurements were also made at designated locations of supply and exhaust air, before and after each series of measurements around the smoke source. Because the digital dust indicator is designed for use in ambient air and not in high velocity air streams, the designated location for measurement of

supply air was near a window vent; the designated location for measurement of exhaust air was adjacent to the main exhaust vents.

A complete series of measurements was made with the smoke source (smoker) in each of the six locations, in one model MCI and one model Prévost bus. For each source location, the smoker was instructed to begin smoking after preliminary measurements were made at the air supply and exhaust sampling locations. The smoker had a cigarette lit and continued smoking until the completion of the series of measurements. The vehicle was then ventilated (open door and roof hatch) until airborne particulate concentrations returned to background levels. Then, another series of measurements was begun. Upon completion of the six series of measurements in each vehicle, one or more repeat series was done.

3.2 Results

The one minute concentrations of airborne respirable particulate in counts per minute (cpm), measured sequentially at various locations around a smoker (smoke source) are summarized in Table 4-1 (MC9 vehicle) and Table 4-2 (Prévost vehicle). As can be seen from these tables, background concentrations of respirable particulate are in the range of 8 - 15 cpm. A series of one minute measurements taken at the exhaust sampling location after the first cigarette was lit demonstrated marked increases within one to two minutes. Peak concentrations of up to 249 cpm respirable particulate occurred in the seat beside the smoke source. Concentrations at other nearby seats generally ranged from 30 - 90 cpm. Concentrations in supply air (29-78 cpm) were often not markedly different from those in exhaust air (29-88 cpm).

TABLE 3-1
CONCENTRATIONS OF AIRBORNE RESPIRABLE PARTICULATE (IN COUNTS PER MINUTE) MEASURED SEQUENTIALLY AT VARIOUS LOCATIONS AROUND A SMOKER (SMOKE SOURCE), MC9 VEHICLE

Measurement Location	LOCATION OF SMOKER							
	Row 2 L-Window	Row 3 R-Aisle	Row 5 L-Aisle	Repeat	Row 6 R-Window	Repeat	Row 9 R-Aisle	Row 10 L-Window
Supply	8 *	9	9 *	8	9 *	10	9	10
Exhaust	33	8 *	35	8 *18,28	22	10 *11,22,37	10 *11,19,25	10 *14,21,48
Adjacent Seat	32	166	241	126	47	63	78	48
Seat in Front								
• Window	210	49	84	65	62	74	58	50
• Aisle	63 *	43	89	87	63	73	58	56
Seat Behind								
• Window	47	33	47	50	71	71	64	54
• Aisle	55	33	44	75	81	73	90	55 *
Seat Across Aisle		*						
• Behind		43	41 *	68 *			67	
• Beside		42	106	100			119 *	
• In Front		41	72	79			68	
Adjacent Seat	69 *	179	85	249	74	80	149	71
Exhaust	109	57	46	63	52	61	55	43
Supply	78	50 *	45	51	55	51	54	48
Exhaust	88	65	53	63	63	55	61	47

Note: * Indicates when new cigarette started.

TABLE 3-2
CONCENTRATIONS OF AIRBORNE RESPIRABLE PARTICULATE (IN COUNTS PER MINUTE)
MEASURED SEQUENTIALLY AT VARIOUS LOCATIONS AROUND A SMOKER (SMOKE SOURCE), PREVOST VEHICLE

Measurement Location	LOCATION OF SMOKER						
	Row 2 R-Aisle	Row 2 L-Window	Repeat	Row 6 L-Aisle	R-Window	Row 10 L-Window	Row 11 R-Aisle
Supply	11	11	10	10	15	12	12
Exhaust	11 *25,39,53	11 *52,54	10 *28,41	10 *23,28	15 *17,34	10 *11,17	11 *12,20
Adjacent Seat	182	182	60	42	68	39	84
Seat in Front • Window • Aisle	 59 87	 63 73	 43 52	 31 41	 55 65	 41 48	 44 50
Seat Behind Window • Aisle	 71 74	 75 59 *	 44 43	 55 45	 72 68	 48 46	 51
Seat Across Aisle • Front • Behind	 105 73 *			 37 44 *	 *		 56 68
Adjacent Seat	198	108	121	45	82	52	207
Exhaust	61	57	58	46	56	27	31
Supply	60	45	32	63	52	29	35
Exhaust	67	72	44	51	47	29	33

Note: * Indicates when new cigarette started.

3.3 Discussion

Each smoke concentration measurement at a location around a smoke source (smoker) gives a one minute respirable particulate concentration at a single point in space. A great deal of variability can be expected in individual measurements, because of the numerous uncontrolled variables affecting the smoke emission rates and dispersion patterns, such as:

- the burn rate of the cigarette;
- the position in which the cigarette is held;
- the way inhaled smoke is exhaled; and
- turbulent air flow patterns.

Therefore, it is important to consider the measurements summarized in Tables 3-1 and 3-2 in a general way, and not to put a great deal of significance on individual results or pairs of results.

The variability of individual measurements can be seen in the series of repeat measurements in each vehicle. Differences in results at any one measurement location range from less than 10% to over 90%, with the largest differences occurring at the location of highest smoke concentration. This lack of reproducibility in single sets of results is not unexpected, but does suggest that it is the overall pattern in the results which provides information of significance.

The overall pattern of results indicates the following:

1. The effect of one cigarette anywhere in the bus was noticeable at the exhaust in under one to two minutes. This is an indication of rate of air movement through the bus.

2. Smoke concentrations were usually highest at the seat adjacent to the smoke source (smoker). Occasionally however, because of localized air channelling and/or the position in which a cigarette is held, concentrations at another seat were greater.

3. Smoke concentrations in "supply" air were similar to or slightly less than concentrations in "exhaust" air. This suggests that mixing occurred in the passenger compartment (rather than in the recirculation system) and that smoke removal mechanisms were few.

4. Concentrations of respirable particulate in the "supply" air increased five-fold (relative to fresh outside air) after sequential smoking of two cigarettes (supply air in the range of 50 $\mu g/m^3$, relative to fresh outside air 10 $\mu g/m^3$). Concentrations of respirable particulate in excess of approximately 50 $\mu g/m^3$ in office buildings are generally associated with increased complaints concerning air quality.

4.0 AIR QUALITY VARIATIONS IN SMOKING AND NON-SMOKING BUSES

The objectives of this task were to monitor several indicators of air quality at numerous locations throughout a bus, during normal intercity operation on smoking and non-smoking runs. Parameters to be monitored were respirable particulate, carbon dioxide, temperature and relative humidity. These parameters were selected because of the relative simplicity in monitoring them, and because of their direct association with occupancy levels, passenger comfort, and smoking.

Intercity runs selected for testing were those which would allow approximately eight hours sampling time for each of smoking and non-smoking runs. The characteristics of these runs (passenger loads, travel times) are summarized in Table 4-1. Sampling was done continuously during travel time; sampling was stopped when unloading passengers and standing in the terminal. The measurement methods and results are described in the following sections.

4.1 Measurement Methods

4.1.1 Respirable Particulate

Respirable particulate concentrations were monitored in six (6) locations throughout the bus, using two different methods. The first was the most commonly used method of determining time-weighted average concentrations of respirable particulate. A pre-calibrated battery-operated pump draws air at a rate of 1.7 litres per minute through a sampling head consisting of a cyclone (to separate out larger, so-called "non-respirable" particles from the airstream), in line with a pre-weighed filter (Teflon 37 mm diameter). Upon completion of sampling, the filter was analyzed gravimetrically to determine weight gain during a known sampling period. The analytical result was expressed in micrograms per cubic meter ($\mu g/m^3$), the average respirable particulate concentration during the sampling period.

TABLE 4-1

CHARACTERISTICS OF INTERCITY TRIPS DURING TESTING

Non-Smoking Run (14 November 1986)		
Ottawa to Montreal	0700 - 0913	33 Passengers
- Express		
Montreal to Ottawa	1250 - 1453	Full Load
- Stopped at Pointe Clair for last six passengers		
Ottawa to Montreal	1650 - 1915	Full Load
Montreal to Ottawa	1930 - 2140	40 Passengers

Note: Although non-smoking runs are clearly marked as such, several persons were observed to smoke at their seats or in the washroom.

Smoking Run (16 November 1986)		
Ottawa to Toronto	1135 - 1600	30 Passengers (about 7 were smokers)
Toronto to Ottawa (Via Kingston to change drivers at 1915)	1650 - 2130	40 Passengers (about 5 were smokers)

The second method involved real time analysis of airborne respirable particulate, using the Sibata digital dust indicator described in Section 3.1. The analytical results were expressed as counts per minute (cpm) during a one minute sampling period.

4.1.2 Carbon Dioxide (CO_2)

Carbon dioxide concentrations were monitored in two locations in the bus approximately every hour, using two different sampling methods, both giving instantaneous readout. The first was the HORIBA (Model APBA-210) portable CO_2 monitor, which determines carbon dioxide concentrations by infrared analysis. The second was GASTEC ANALYZER tubes (2LL, #060636), which develop a length of stain in proportion to the concentration of CO_2 in the sampled air. The two sampling methods were used simultaneously, as a check on analytical results.

4.1.3 Temperature and Relative Humidity

Temperature and relative humidity were monitored in three locations in the bus, approximately every half hour. Measurements were made using dry bulb and wet bulb thermometers.

4.2 Results

4.2.1 Respirable Particulate

The respirable particulate concentrations observed by filter collection and gravimetric analysis, summarized in Table 4-2, were generally below the detection limit of the method. The detection limit was determined by calculating the filter weight gain required to be considered statistically significant (with a 95% confidence limit). As the field blank had an apparent weight gain of 0.18 mg, any

TABLE 4-2

TIME-WEIGHTED AVERAGE CONCENTRATIONS OF RESPIRABLE PARTICULATE DURING INTERCITY RUNS

Sample Location	Duration (Min.)	Volume (L)	Change In Filter Wt. (mg)	Average Concentration ($\mu g/m^3$)
(a) Non-Smoking Run				
Row 1 Right	575	983	+0.06	NS
Row 2 Left	575	972	+0.05	NS
Row 5 Right	573	986	-0.03	NS
Row 6 Left	561	951	+0.09	NS
Row 8 Right	560	941	-0.19	NS
Row 9 Left	558	954	+0.03	NS
(b) Smoking Run				
Row 1 Right	588	1005	+0.04	NS
Row 2 Left	588	1000	+0.18	NS
Row 5 Right	590	1015	-0.02	NS
Row 6 Left	589	995	+0.04	NS
Row 8 Right	590	991	+0.10	NS
Row 9 Left	591	1011	+0.36	360
Field Blank	-	-	+0.18	-

NOTE: NS indicates not statistically significant.

weight gain less than 0.29 mg was not considered statistically significant. Therefore, the detection limit of the method was 290 $\mu g/m^3$. Only one sample taken during the smoking run exceeded this with a result of 360 $\mu g/m^3$.

Respirable particulate concentrations observed with the respirable particle counter are summarized in Table 4-3. These ranged from 7-17 cpm on the non-smoking runs and 15-343 cpm on the smoking runs (*Several observations of higher values, 20-55 cpm on the non-smoking runs, were associated with a smoker.

4.2.2 Carbon Dioxide Concentration

Carbon dioxide concentrations are summarized in Table 4-4. They were observed to range from 1200-2000 ppm on the non-smoking runs, and 1000-1600 ppm on the smoking runs.

4.2.3 Temperature and Relative Humidity

Air temperatures are summarized in Table 4-5. They ranged from 21.0°C and 23.0°C-28.0°C on different trips.

Relative humidity values are summarized on Table 4-6. They ranged in general from 28%-47% (one reading of 58% may have resulted from reading error).

4.3 Discussion

4.3.1 Respirable Particulate

The filter collection and gravimetric analysis method for respirable particulate does not have low enough detection limits for anticipated concentrations in the range of 100 $\mu g/m^3$, unless the sample volumes are greater than 2000 to 3000 L,

TABLE 4-3

REAL TIME CONCENTRATIONS OF RESPIRABLE PARTICULATE (EXPRESSED IN COUNTS PER MINUTE OR CPM) DURING INTERCITY RUNS

(a) Non-Smoking Run

	Sample Location					
Time	Row 1-R	Row 2-L	Row 5-R	Row 6-L	Row 8-R	Row 9-L
0715	10	9	8	9	8	8
0745	7	8	8	7	7	7
0815	8	8	8	8	9	8
0845	10	10	11	11	11	11
1300	15	15	11	11	11	10
1345	8	8	8	26*	55*	35
1415	27*	20*	16	12	11	10
1445	7	7	7	7	8	8

Note: * Indicates smoker observed at back of bus.

1730	9	10	-	-	-	8
1800	9	8	10	16	13	12
1830	9	11	11	9	8	10
1850	10	12	12	10	11	10
1935	13	13	16	12	17	-
2000	10	10	9	9	9	10
2030	11	10	11	9	9	12
2100	9	11	9	9	10	16

TABLE 4-3

REAL TIME CONCENTRATIONS OF RESPIRABLE PARTICULATE (EXPRESSED IN COUNTS PER MINUTE OR CPM) DURING INTERCITY RUNS (Cont'd)

(b) Smoking Run

	Sample Location					
Time	Row 1-R	Row 2-L	Row 5-R	Row 6-L	Row 8-R	Row 9-L
1150	145	159	127	86	66	49
1215	17	39	76	65	114	249
1235	63	21	18	22	25	33
1300	135	156	109	101	71	55
1315	57	160	144	133	189	136
1335	67	71	59	45	39	30
1355	33	28	22	22	17	16
1420	42	68	77	92	95	62
1440	56	69	87	72	57	34
1500	19	16	17	16	15	48
1515	35	59	80	106	116	136
1535	42	70	76	82	90	93
1710	30	60	120	164	214	155
1735	22	53	68	96	265	198
1815	47	38	32	25	22	19
1830	176	251	343	322	148	117
1900	42	56	78	97	106	94
1930	54	37	28	20	16	16
2000	138	177	201	210	201	132
2030	90	114	157	145	140	159
2100	97	146	160	137	194	196

TABLE 4-4

CARBON DIOXIDE CONCENTRATIONS
(EXPRESSED IN PARTS PER MILLION OR PPM)
DURING INTERCITY RUNS

(a) Non-Smoking Run

	Location	
Time	Row 1-R	Row 8-R
0715	1400	1500
0815	1300	1300
1300	1600	1700
1415	1500	1400
1700	1700	1800
1800	1750	1750
1900	2000	1800
2000	1400	1300
2100	1400	1200

(b) Smoking Run

	Location	
Time	Row 1-R	Row 8-R
1145	1500	1350
1245	1250	1600
1315	1200	1500
1355	1400	1400
1440	1250	1200
1515	1200	1400
1535	1450	1600
1700	1400	1500
1735	1250	1300
1830	1200	1400
1930	1000	1400
2030	1000	1200

TABLE 4-5

TEMPERATURE (IN ^{o}C)

DURING INTERCITY RUNS

(a) Non-Smoking Run

	Location		
Time	Row 1-R	Row 5-R	Row 8-R
0715	21.5	24.0	24.0
0815	22.5	24.0	24.0
0845	21.5	22.5	22.0
1300	23.0	22.0	22.0
1345	23.5	24.0	24.0
1415	23.5	23.0	24.0
1445	25.0	25.0	25.0
1705	22.0	25.0	25.0
1805	24.0	25.0	25.0
1850	25.0	25.0	26.0
2000	26.0	26.0	25.0
2100	25.0	25.0	25.0

TABLE 4-5

TEMPERATURE (IN ^{0}C)

DURING INTERCITY RUNS (Cont'd)

(b) Smoking Run

	Location		
Time	Row 1-R	Row 5-R	Row 8-R
1145	23.0	23.0	24.0
1235	25.0	25.0	26.0
1315	26.0	26.5	26.5
1355	26.0	26.0	26.0
1440	27.0	27.0	27.0
1515	27.0	27.0	27.0
1535	28.0	27.0	27.0
1635	21.0	20.0	21.0
1710	25.0	23.0	25.0
1735	25.0	25.0	23.0
1830	25.0	23.0	25.0
1930	23.0	24.0	24.0
2030	25.0	25.0	27.0
2100	25.0	27.0	27.0

TABLE 4-6

RELATIVE HUMIDITY (IN %)

DURING INTERCITY RUNS

(a) Non-Smoking Run

	Location		
Time	Row 1-R	Row 5-R	Row 8-R
0715	38%	28%	28%
0815	32%	28%	28%
0845	32%	31%	33%
1300	32%	36%	36%
1345	33%	33%	31%
1415	30%	32%	34%
1445	32%	34%	34%
1705	42%	30%	34%
1805	34%	34%	34%
1850	34%	34%	36%
2000	36%	36%	40%
2100	58%	58%	58%

TABLE 4-6

RELATIVE HUMIDITY (IN %)

DURING INTERCITY RUNS (cont'd)

(b) Smoking Run

	Location		
Time	Row 1-R	Row 5-R	Row 8-R
1145	44%	39%	38%
1235	34%	34%	30%
1315	36%	29%	28%
1355	34%	36%	36%
1440	34%	36%	36%
1515	37%	42%	48%
1535	38%	42%	42%
1635	47%	46%	47%
1710	46%	44%	34%
1735	30%	34%	44%
1830	34%	41%	46%
1930	44%	38%	36%
2030	32%	32%	26%
2100	32%	28%	26%

(2 to 3 m^3). As the sampling equipment is limited to a flow rate of 1.7 Lpm, sample times in the range of 20 to 30 hours are necessary. Therefore, although this is the most commonly applied sampling and analytical method for respirable particulate in indoor environments, it is not ideally suited to measurements in moving vehicles.

Respirable particulate concentrations observed with the respirable particle counter in counts per minute (cpm) may be considered roughly equivalent to $\mu g/m^3$, because the size distribution of cigarette smoke particulate is in the same range as that of the aerosol used to calibrate the instrument. The measurements indicated average concentrations in the range of 12 $\mu g/m^3$ during non-smoking runs, and average concentrations in the range of 70-100 $\mu g/m^3$ during smoking runs. These may be compared with concentrations of 5-20 $\mu g/m^3$ commonly found in outdoor air, concentrations of 20-50 $\mu g/m^3$ in indoor air, and concentrations of greater than approximately 60 $\mu g/m^3$ in offices which are often associated with complaints of air quality.

There was a significant difference in average respirable particulate concentrations in non-smoking and smoking runs (12 $\mu g/m^3$ vs. 70-100 $\mu g/m^3$). Concentrations during smoking runs varied substantially during the runs, presumably associated with varying rates of cigarette smoke emission. Average concentrations of respirable particulate throughout each smoking run were significantly lower in the front seat (Row 1-R) than in other measurement locations.

4.3.2 Carbon Dioxide

Potential errors in the carbon dioxide readings are in the range of 15 to 30%. Therefore, there were no significant increases in carbon dioxide concentrations in smoking runs relative to non-smoking runs. However, concentrations of 1700 ppm or higher were only associated with full passenger loads. Carbon dioxide concentrations consistently exceeded 1000 ppm. Although not directly applicable to the transportation industry, the Ontario Ministry of Labour considers that

carbon dioxide concentrations in excess of 1000 ppm in office buildings are indicative of insufficient fresh air.

4.3.3 Temperature and Relative Humidity

Temperatures in the range of 20°C to 25°C and relative humidities in the range of 40% to 60% are generally considered comfortable for persons at rest, exposed to little radiant heat. Observed temperatures were never less than 20°C; however, they exceeded 25°C approximately 24% of the time (22 of 90 observations). Relative humidities fell within the comfort range 24% of the time (19 to 78 observations), but were generally slightly below, in the range of 30 to 40%. These results compare favourably to relative humidities commonly found in buildings in eastern Ontario, western Quebec during winter (heating) season.

5.0 ALTERNATIVES TO IMPROVE AIR QUALITY

5.1 General Problem Statement

In the foregoing sections, the air flows relevant to the heating, ventilating and air conditioning process were thoroughly characterized and key air quality parameters were measured. Briefly, this measurement effort produced the following results:

- Outdoor air component of 8 to 9% of air supplied to passenger compartment (4 to 5 cfm/person);
- Air velocities inside the passenger compartment ranging from 20 to 110 fpm;
- Air supply and return configurations which cause passenger compartment air flow through several rows of seats;
- Left to right side supply air imbalance: side to side flow differences of 17 to 37%;
- The effect of one cigarette anywhere in the coach was noticeable at the exhaust in under one or two minutes;
- Smoke concentrations in supply air were similar to or slightly less than concentrations in exhaust air. This suggests completely ineffective filtering.
- Respirable particulate concentrations of about 12 $\mu g/m^3$ during actual non-smoking runs, and average concentrations in the range of 70 to 100 $\mu g/m^3$ during actual smoking runs. One third of readings exceeded 100 $\mu g/m^3$.
- Carbon dioxide levels consistently exceeded 1000 ppm and concentrations of 1700 ppm or higher were associated with full passenger loads.
- Temperature and humidity were largely within an acceptable range.

5.2 Target Air Quality Parameters

The intercity coach heating, ventilating and air conditioning system should be designed to satisfy the following comfort and air quality parameters:

Temperature	:	20° to 25°C
Humidity	:	40% to 60%
Interior Air Speeds	:	20 to 50 fpm
Respirable Particulate	:	less than 100 $\mu g/m^3$
Carbon Dioxide	:	less than 1000 ppm

The temperature and humidity ranges presented are generally considered comfortable for persons at rests, exposed to little radiant heat. While the low end of the temperature parameter of 20° might appear low for people at rest, it was selected with consideration for the fact that passengers board coaches during the heating season dressed for the outdoors. From the measurement work in Chapter Four it is evident that the comfort targets of temperature and humidity are largely satisfied.

The interior air speed parameter if respected should minimize any complaints of stale air or drafts. The target range suggested for air speed is compatible with the comfort criteria described in the ubiquitous "Carrier Handbook of Air Conditioning System Design: and recent research performed by Fanger and Christensen (1985).

The target air quality parameter suggested for respirable particulate was chosen in accordance with the concentrations of limited or no concern for Tobacco smoke (passive smoking) published by a working group on indoor air quality research of the World Health Organization. An additional indoor air standard for particle density in office buildings is the Japanese standard of 150 $\mu g/m^3$. Health and Welfare Canada have published exposure guidelines for residential indoor air quality which refer to tobacco smoke and respirable particulate matter with a similar particle size distribution to tobacco smoke. The government of

Canada guideline suggests acceptable short term exposure to respirable particulate be less than 100 $\mu g/m^3$ and long term exposure be less than 40 $\mu g/m^3$. As previously stated in Chapter Four, based on this research team's experience studying "sick buildings", that complaints can be expected when respirable particulate levels exceed about [illegible] $\mu g/m^3$.

The proposed target for Carbon Dioxide of less than 1000 ppm (1800 $\mu g/m^3$) corresponds to what is suggested in: ASHRAE standard 62-1989, the Japanese standard for indoor office environments and the concentrations of limited or no concern published by a working group on indoor air quality research of the World Health Organization. Carbon dioxide concentration has been widely used as an indicator of indoor air quality. The proposed limit of 1000 ppm is recommended to satisfy comfort (odour) criteria. In the event that carbon dioxide is controlled by any method other than dilution, the effects of the possible elevation of other contaminants must be considered.

Research at the John B. Pierce Laboratory by W.S. Cain, et al, and at the Technical University of Denmark by B. Berg-Munch, et al, has shown that about 15 cfm (7.5L/S) of outdoor air per person is needed to dilute occupant odours to a level acceptable to 80 percent of the visitors first entering the space. The research shows that 15 cfm of outdoor air brings the room CO_2 down to 1000 ppm[1].

5.3 The HVAC process

To better understand the variables and parameters of the HVAC process specific to conventional coaches, a simplified, schematic representation was developed in Figure 5.1.

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[1] Leaderer, B.P. and W.S. Cain, "Air Quality in Buildings During Smoking and Non-Smoking Occupancy", ASHRAE Trans. V89, PT2A&B, 1983.

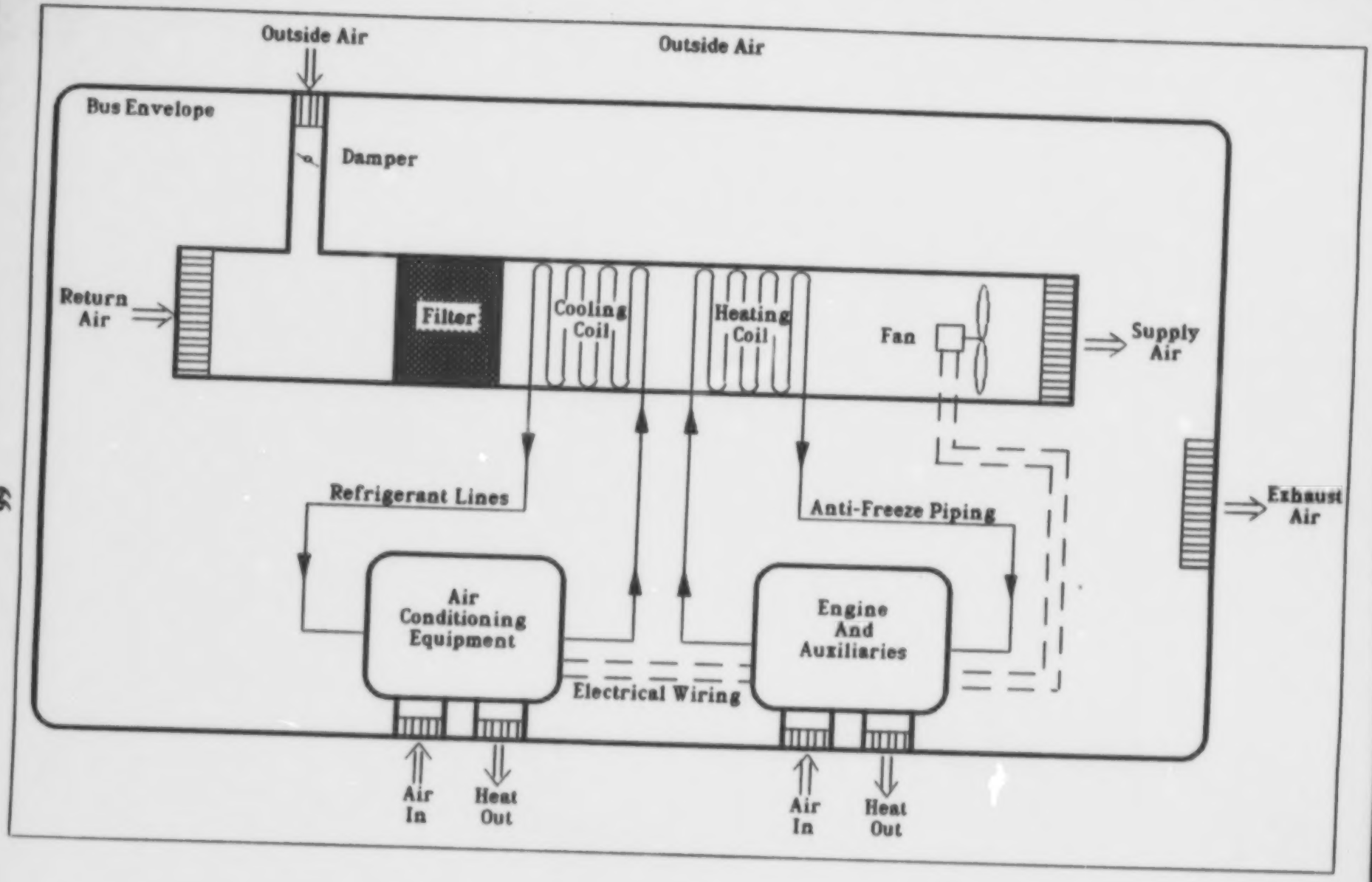

Figure 5.1
The HVAC PROCESS
IN CONVENTIONAL COACHES

Key variables in the design of an HVAC system include percent outdoor air and percent removal of contaminants from recycled air.

Physical limitations of conventional buses associated with modifications of these key variables include:

1) Passenger compartment must be pressurized to satisfy and noise and dust infiltration considerations;

2) Total draw on alternator must be less than 270 amps;

3) Heat output at fast idle;

4) 7.5 ton nominal capacity of air conditioning system;

5) Windows must not fog up.

In order to satisfy the air quality parameters presented previously, the production and loss of contaminants must balance below the acceptable thresholds under design conditions. A simple mathematical model which suits this application is based on the general mass balance approach. When all mechanisms for the productions and loss of contaminants are accounted for properly the change in concentration per unit time is defined by:

$$\frac{dC}{dt} = P - LC \qquad (1)$$

where C = concentration of contaminants
t = time
P = rate of production of contaminants
L = rate of loss of contaminants

at equilibrium, $\frac{dC}{dt} = 0$, or the production rate equals the loss rate. Solving for the concentration gives:

$$C = \frac{P}{L} \qquad (2)$$

Production mechanisms include contaminant presence in outdoor air and local source (passengers). Loss mechanisms include exhaust and leakage rates, deposition rates and air cleaning mechanism capture rate.

5.4 Development of Alternatives

5.4.1 Increase Outdoor Air Supply

Under full passenger load, outdoor air supply would have to be increased from roughly 250 cfm to 500-700 cfm if the CO^2 threshold of 1000 ppm is to be respected. according to the detailed load calculations in Appendix B, the 700 cfm outdoor air flow rate would represent a cooling load increase of about 15,000 Btu/h and a heating load increase of about 50,000 Btu/h.

The increased cooling load would not be a problem under Canadian climatic conditions but the increase in heat load does represent a problem based on information acquired through discussion with Detroit Diesel Allison. The 6V92 engine has a gross heat output at fast idle (900 rpm) of approximately 94,500 Btu/h assuming parasitic loads of 6.6% of BHP. This represents a shortfall of at least 35,000 Btu/h since losses associated with delivering this engine heat to the passenger compartment are not accounted for.

Some conventional buses are equipped with optional diesel fuelled water heaters to complement engine heat in extremely cold climates. This same technology could be used to complement engine heat when this increased ventilation heating load is added.

Another impact of increased outdoor air would be a reduction in relative humidity but this would reduce the possibility of unwanted condensation on windows.

In order to permit more outdoor air supply, buses would have to be modified to allow more exhaust and less flow restrictions on outdoor air intakes. Although

an increase in exhaust flow is required, the modifications must still maintain sufficient positive pressure within the vehicle.

In our estimation, conventional equipment used in buildings would facilitate the controlled exhaust required in buses. A variable air volume box similar to the "Hart and Cooley" HCS-1 model would control the amount of air exhausted independently of pressure differences. The HCS-1 has a flow sensing device, controller and actuator which will continuously monitor and maintain the required air quantity regardless of the pressure difference across the device. This exhaust controlling device measures only 360 x 360 x 250 mm and would be located underneath the floor. It would be connected through ducting to an exhaust grille located underneath a passenger seat or along the wall at the floor. A relief grille would be required to allow the exhaust air to escape from the battery or luggage compartment.

An in-line regulator would be required to reduce the existing 90 psi pneumatic supply air to the 10 to 20 psi range required by the device.

5.4.2 Increase Removal of Contaminants from Inside Air

The air change created by the ventilation system is about one air change per minute. The existing filter compartment is in the mixing box immediately upstream of the heating and cooling coils. Ideally one would like to take advantage of this high air movement rate by upgrading the existing filter to remove more contaminants from the recycled air. This would minimize impacts on the limitations of conventional bus equipment. Without any changes to the overall dimensions of the mixing box, there is room for a 50 mm thick filter.

5.4.2.1 Alternate 50 mm Filters

Three alternate 50 mm filters were considered and will be briefly described.

AAF AM AIR 600
DYNAMIC FILTER
DISPOSABLE FIBREGLASS/ACTIVATED CHARCOAL
LAMINATED FILTER (UNDER DEVELOPMENT)

The first two alternates develop a final resistance to air flow under 300 Pa (1.2 w.g.). The final option is still under development and testing is not complete.

The resistance to air flow which the first two would develop is about double that developed by the existing filter. The existing filter is comprised of three layers of pleated insect screen in . 500 x 940 mm frame.

The advantages of the first alternate is its simplicity of installation. According to some recent research at the university of Waterloo this type of filter has a single pass particle collection efficiency on particulate in the range of 0.3 - 0.5 mm diameter of about 18%. This throwaway filter should be changed whenever the pressure drop exceeds 250 Pa.

The Dynamic Filter is a non-ionizing electronic filter and offers a higher collection efficiency but requires power at 24 VDC. This should not represent a significant problem since lights and other electrical equipment on conventional coaches are powered with 24 V circuits. The power consumption of the 50 mm Dynamic Filter is negligible at 2 W. The Waterloo research tested the 25 mm model but still showed a 22% higher collection efficiency. The 50 mm model should provide slightly improved collection efficiencies.

A limiting factor which should be explored further has to do with the electronic advantage of the filter being negated when electrically conducive particulate are captured by the filter. These conducive particles cause short circuiting within the

filter and reduce its efficiency to a simple 50 mm 4% fibreglass media filter. Carbon is one conducive dust particle which could likely cause this short circuiting but it is not know if it is present in any significant quantities to precipitate this apparent shortcoming. Another factor which may negate the electrostatic advantage is the electrostatic charge developed in the moving vehicle. Because the existing pleated insect screen filter is metallic it may already benefit from an electrostatic advantage.

The disposable fibreglass/activated charcoal laminated filter currently under development at Circul-Aire Inc. laboratories would offer gas phase performance as well as particulate phase performance. The activated charcoal could be formulated to capture gas phase contaminants of interest. The chemical formulation could be different for say a non-smoking bus.

5.4.2.2 High Capacity Filters

Bus manufacturers are always in the process of developing vehicles which require less maintenance and have succeeded in extending most maintenance intervals in the last few years. The 50 mm filtration options described above would all require more maintenance because of their improved contaminant capturing capabilities. From an operator's point of view this would negate somewhat any improvement in air quality which would be achieved.

If more space could be made available for the filtration section, higher capacity and higher efficiency bag-type filters could be used. An adequate extension of the filtration section to accommodate this technology would amount to about 350 mm. The main advantages to these larger, high capacity filters are much improved performance and no change in maintenance interval. The pre-filter section usually associated with high-performance filters for economic reasons would have about the same maintenance intervals as the existing filter used on coaches and the high efficiency section would have a maintenance interval of some three to six months depending on conditions.

The disadvantages are: the space requirement would encroach on revenue generating baggage/parcel space and higher maintenance costs would result.

Research on aircraft has shown that the high efficiency filtration systems currently in use on modern passenger airliners equipped with recirculation systems have substantially reduced irritation associated with tobacco smoke.[2,3]

5.4.3 Improve Interior Aerodynamics

From the work in Chapter Two interior air speeds are slightly on the high side. The bus model with the better balanced ventilation system had significantly lower head level air speeds (26 fpm left side, 39 fpm right side vs 50 fpm left side, 33 fpm right side). The more obvious differences between the two models tested were: supply air balance left to right and distribution of return air grilles. The left to right supply air balance should be easily corrected with the addition and adjustment of a balancing damper. The extent of the return air system is much more difficult to retrofit and would have to wait for the next generation of coach.

There are two underlying reasons why air speeds are on the high side in conventional coaches. First, the heating and cooling system designs in coaches rely solely on air changes to perform the heating and cooling. Second, the defogging/defrosting of passenger windows is an important design consideration that has caused higher than comfortable velocitites. Some alternatives which would help reduce interior air velocities on next generation coaches would include: reducing loads by better insulating the bus envelope, reducing solar loads by selecting more reflective glazing and a vented roof skin, establishing a radiant heating system near the perimeter perhaps in the floor.

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[2]Newman, W.H. and M.R. Viele. Engine Bleed Air Reduction in DC-10. NASA-CR-159846. Long Bech, Cal.: Douglas Aircraft Company, 1980.

[3]Weber, R. Travel Involving long-distance flights: health risks. Med. Monatsschr. Pharm. 7(5):147-151, 1984. (in German)

5.4.4 Eliminate Smoking

As described in the previous sections exposure to Environmental tobacco smoke (ETS) can be minimized through improved dilution with outdoor air and improved filtration. Unfortunately, compact, high-performance, economical filter systems that effectively remove gases and particles associated with ETs and are compatible with requirements for installation on existing coaches have not yet been developed. Improved dilution requires expensive alterations to existing coaches to respect the physical limitations and the target comfort parameters listed earlier.

Although these modifications would be more economically introduced in a next generation coach, they involve an increase in operating costs which may not be acceptable to operators.

As an alternative to improve air quality on intercity coaches, a ban on smoking would offer several important advantages. Prohibiting smoking should reduce cleaning costs, and the costs of replacing and repairing damaged materials. Removing tobacco smoke from the coach environment would reduce irritation, health risks, and completely satisfy the target comfort parameter associated with respirable particulate.

In a 1985 Gallup poll[4], over 85% of non-smokers and 60% of smokers felt that smoking should be restricted in the workplace and that, in the presence of non-smokers, smokers should curtail their smoking.

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[4] American Lung Association. "Americans Want Smoke-Free Air at Work". New York, N.W.: American Lung Assoc., Dec. 1985.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following opinions are based objectively upon the facts presented in this report:

1. On both the MCI MC9 and the Prévost Marathon XL, the fresh air volume flow rate was less than 10% of the total conditioned air flow, compared to the manufacturer specified value of 20%.

2. The fresh air intake on the MC9 coach is adjustable between 1.3% and 8.0% of the conditioned air flow. **Under normal operating conditions, the fresh air damper is fully closed, such that the fresh air intake is only 1.3% of the conditioned air flow.**

3. The fresh air intake on the Marathon XL coach is adjustable between 7.9% and 9.1% of the conditioned air flow. Thus, the five damper settings on the fresh air intake have the capacity to vary the fresh air supply by only 1.2% of the conditioned air flow.

4. The measured exhaust air flow on both of the coaches was below 4% of the exhaust flow. This means that more than half of the exhaust flow for both coaches is due to leakage around various window, door and other seals.

5. Highway speed operation introduced only minor changes in the flow rates and flow patterns of the two coaches.

6. Tests conducted with passengers demonstrated that the flow characteristics of an occupied coach were almost identical to those of an unoccupied coach.

7. It was observed that the differences in flow characteristics between stationary versus highway speed conditions and occupied versus unoccupied conditions were of the same order of magnitude as the flow differences between various coaches of the same model.

8. The conditioned air flow patterns were found to be uniform and symmetrical in the MC9 coach. In the Marathon XL coach, a stronger flow existed on the right side of the coach and the longitudinal distribution of air from the diffusers was not uniform.

9. In the MC9 coach, the front aisle return ducts accounted for 67% of the total return flow and the from aisle and wall return ducts together accounted for 81% of the total return flow.

10. The general air flow patterns in the MC9 coach indicate an overall forward flow tendency (towards the door exhaust port and the from return ports). The general air flow patterns in the Marathon XL indicate a general flow towards the centre of the coach (where the single return air port is located).

11. The fresh air is evenly mixed with the return air in both coaches and consequently, the fresh air distribution follows the same pattern as the conditioned air distribution.

12. The driver's air conditioning system had only a minor effect on the overall flow characteristics for both of the coaches. This consisted of an increase in turbulence in the front portion of the passenger compartment.

13. The effect of one cigarette anywhere in the bus was noticeable at the exhaust in under one to two minutes. This is an indication of rate of air movement through the bus.

14. Smoke concentrations were usually highest at the seat adjacent to the smoke source (smoker). Occasionally however, because of localized air channelling and/or the position in which a cigarette is held, concentrations at another seat were greater.

15. Smoke concentrations in "supply" air were similar to or slightly less than concentrations in "exhaust" air. This suggests that mixing occurred in the passenger compartment (rather than in the recirculation system) and that filtration devices are largely ineffective.

16. Concentrations of respirable particulate in the "supply" air increased five-fold (relative to fresh outside air) after sequential smoking of two cigarettes (supply air in the range of 50 $\mu g/m^3$, relative to fresh outside air 10 $\mu g/m^3$.

17. Respirable particulate concentrations observed with the respirable particle counter in counts per minute (cpm) may be considered roughly equivalent to $\mu g/m^3$, because the size distribution of cigarette smoke particulate is in the same range as that of the aerosol used to calibrate the instrument. The measurements indicated average concentrations in the range of 12 $\mu g/m^3$ during non-smoking runs, and average concentrations in the range of 70-100 $\mu g/m^3$ during smoking runs. One-third of the readings exceeded 100 $\mu g/m^3$. These may be compared with concentrations of 5-20 $\mu g/m^3$ commonly found in outdoor air, concentrations of 20-50 $\mu g/m^3$ in indoor air, and concentrations of greater that approximately 60 $\mu g/m^3$ in offices which are often associated with complaints of air quality.

There was a significant difference in average respirable particulate concentrations in no-smoking and smoking runs (12 $\mu g/m^3$ vs. 70-100 $\mu g/m^3$). Concentrations during smoking runs varied substantially during the runs, presumably associated with varying rates of cigarette smoke emission. Average concentrations of respirable particulate throughout each smoking run were significantly lower in the front seat (Row 1-R) than in other measurement locations.

18. Potential errors in the carbon dioxide readings are in the range of 15 to 30%. Therefore, there were no significant increases in carbon dioxide concentrations in smoking runs relative to non-smoking runs. However, concentrations of 1700 ppm or higher were only associated with full passenger loads. Carbon dioxide concentrations consistently exceeded 1000 ppm which is generally indicative of insufficient outdoor air.

19. Temperature and relative humidity were largely within an acceptable range.

20. Compact, high-efficiency, economical filter systems that effectively remove gases and particles associated with tobacco smoke which are compatible with requirements for installation on existing coaches have not yet been developed.

6.2 Recommendations

Based on the contents of this report, the following recommendations can be made:

1. The fresh air intake control damper should be set to the full open position on all coaches in order to maximize the fresh air input. **Both MCI and Prévost should communicate technical bulletins to operators informing them that the full open position is recommended and that existing maintenance manuals are wrong in prescribing fully closed.**

2. The adjustable exhaust vent in the door of the MC9 coach should be set to the full open position to maximize stale air exhaust.

3. Measures should be taken to increase the intake and exhaust air flows on both coach models. Intake and exhaust flow rates should be selected to satisfy 1000 ppm CO_2 concentration (about 15 cfm per passenger).

4. In new coaches, measures should be taken to reduce air flow velocities in the vicinity of passengers. This could be accomplished by reducing the total conditioned air flow or by altering the design of the diffusers and/or the ventilation system design.

5. If smoking is to be permitted during intercity travel, special filters or cleaners should be developed to prevent the distribution of pollutants to all coach passengers. In addition, the smoking section should be located at the front of the MC9 coach and in the centre of the Marathon XL coach, to minimize the effect of pollutants on non-smoking passengers.

6. If smoking is to be permitted, serious consideration should be given to allocating more space to the filtration section such that high performance

filtration systems similar to those currently in use on some modern aircraft could be accommodated.

7. On the Marathon XL coaches which have uneven longitudinal ventilation, the Prévost ventilation duct improvement kit can be installed to attenuate the longitudinal air flow distribution. However, qualitative tests conducted on two modified coaches indicate that the kit results in only marginal air flow distribution improvements.

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APPENDIX A

AIR QUALITY STUDY
OF INTERCITY COACHES

January 1987

Prepared For

TRANSPORTATION DEVELOPMENT CENTRE

On Behalf of

DeLCan

By

T E S Limited

Ottawa, Canada

T E S Report Number: C761

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1.0 INTRODUCTION

Air quality in intercity buses has a significant influence on passenger comfort and satisfaction, and poor air quality is an issue of great concern to bus operators and manufacturers. To date, little investigation or experimental work has been performed to determine the causes of poor air quality or methods of improving it. With the increasing number of complaints regarding air quality in intercity buses, the Transport Development Centre (Transport Canada) initiated a study of the critical problems relating to air conditioning (air quality and air distribution) on conventional buses. The objectives of the study were to quantify and characterize the status of the air quality in buses and to provide recommendations on improving this air quality. The primary contractor for this study was DeLCan (DeLeuw Cather, Canada, Limited). T E S Limited was subcontracted by DeLCan to measure the air flow distribution characteristics in the test coaches and to provide engineering and technical assistance to the project team during all phases of the study.

To obtain the air flow distribution characteristics in the test coaches, a number of qualitative and quantitative tests were conducted. These tests involved the measurement and illustration of air volume flow rates, air speed and direction at discreet locations, general air flow patterns within the coach, ventilation system balance, fresh air distribution and particle residence times.

This report presents a summary of the work conducted to determine the air flow distribution characteristics of intercity buses. This summary includes the results of the test work, a discussion of these results and appropriate conclusions and recommendations.

2.0 TEST METHODOLOGY

This section of the report describes the development of the test program, from the formulation of the test objectives to the description of the final test procedures.

2.1 Test Objectives

The overall objective of the test program was to determine the air flow distribution characteristics of intercity buses. This broad objective can be defined by a set of more detailed objectives, as follows:

1. Determine the distribution of fresh air and recycled air supplied to the passenger compartment.

2. Determine flow velocities and volume flow rates in the passenger compartment and in the air conditioning system.

3. Determine the air flow patterns in the passenger compartment including an investigation of the effects of passenger occupancy, highway speeds and the driver's air conditioning system and window.

4. Determine temperature distributions in the coach during heating or cooling.

5. Determine particle residence times for pollutant sources located at various positions in the coach.

To attain these objectives, a complete understanding of the operation of the coach air conditioning system is required. Since the coach air conditioning systems generally have the capacity to completely recirculate the air inside the bus within one minute, the air flow patterns are quite complex. In addition, each coach has a multitude of settings and adjustments which can be used to fine tune the coach environment and this increases the complexity of the bus air flow characteristics. The following section discusses the various parameters which were taken into

account during the test program.

2.2 Test Parameters

In intercity buses, there are generally many controls which allow air flows and temperatures to be adjusted and which permit varying amounts of fresh air to be introduced into the bus. With the existence of two independent air conditioning systems in most buses (the driver's system and the passenger compartment system), many combinations of air flows and temperatures are available.

The driver's air conditioning system recirculates air in the front portion of the bus. The recirculated air is conditioned using a heating coil and an evaporator and an adjustable damper allows fresh air to be mixed with the recirculated air. Fresh air is introduced into the system via a vent located under the front windshield. The fresh air damper is normally closed so that the driver is supplied with recirculated air only. A gasper, which is fed with conditioned air from the driver's system, is located in the immediate vicinity of the driver. On some bus models there is a second gasper which can be used to supply (unconditioned) fresh air directly to the driver. On most models, the driver's air conditioning system has a fan speed control and a temperature control and the system can be switched for defroster operation when required. Another option available to the driver is the positioning of the side window. If this window is open, local air flow patterns may be significantly influenced.

The passenger compartment air conditioning and ventilation system can be operated in a heating or cooling mode and the temperature setting is fully adjustable in either mode. The fresh air intake is adjustable by means of a damper and in some buses there is an exhaust vent in the front door which can be operated from a fully open to a fully closed position. In the washroom located at the rear of the coach, there is a window which can be opened or closed, thus causing local changes in the air flow. In addition, the washrooms are vented through the holding tank to prevent any odours from entering the passenger compartment.

Other parameters which were taken into consideration, although not directly related to the operation of the air conditioning systems, include the effects of passenger occupancy and the influence of highway speeds on the air flow characteristics within the coach.

Before defining any specific tests or test procedures, the representative test coaches to be used were determined. A review of the air distribution systems on various intercity coaches indicated that they do not use generically similar systems. For example, the return air porting on the buses was found to be quite different. Prevost Car Inc. models introduce fresh air into the air conditioning system via a single port on the curbside and return air through a single floor duct located centrally on the left hand side of the bus. Motor Coach Industries (MCI), on the other hand, introduce fresh air via two ports, one on each side, and return air through a wall plenum, ported at the front and rear of the coach. On some MCI models, additional return porting is provided in the stepped aisleway at the front of the coach.

An innovative feature of the air distribution system being offered on the new MCI model 102A3 coach is the supply of recycled air through orificed directional nozzles located in the overhead baggage compartments. This system drastically alters the air flow inside the bus (compared to older models), and it will likely become a standard feature on more buses in the near future.

These variations in bus air distribution systems suggest that the test program be conducted on more than one type or model of intercity coach. To take into account the variations between single and multi port exhausting and the introduction of recycled air above the window line on the air flow distribution, three different coaches should be tested. Suitable vehicles for the study would be an MCI 102A3, an earlier MCI model, such as the MC9, and a Prevost Mirage or Marathon XL.

To ascertain the availability of suitable vehicles, a list of the coaches operated by Voyageur Colonial Limited was obtained. A summary of this list appears in Table 1. From this listing, it is evident that the representative test coaches to be used for this program are the MCI MC8

Models	Quantity
G.M.C.	15
MCI, MC7	22
MCI, MC8	67
MCI, MC9	36
Prevost, Marathon	1
Prevost, Marathon XL	10
Total	151

TABLE 1

Voyageur Fleet Distribution Summary (Ontario)

and Prevost Marathon XL. Although the testing of a 102A3 would have presented an interesting variation of the air flow distribution in intercity buses, the unavailability of a sample vehicle prevented any opportunity to conduct tests on a model with an overhead air system. Also, the project objective was to conduct air quality and distribution analysis on conventional intercity coaches. Although Voyageur Colonial operates more MC8 coaches than MC9, the air conditioning systems on these two models are virtually identical, and the later model was chosen for the test program.

The test program concentrated on the MCI MC9 and Prevost Marathon XL coaches. To ensure that the results have wide applicability, part of the test program involved a comparison of coaches of the same model type. This permitted an evaluation of the variability in coach air conditioning system performance, since the degree of variability may have a significant influence on the test results.

2.3 Test Development

In order to evaluate and select an appropriate test methodology, T E S Limited contacted personnel at the Low Speed Aerodynamics Section of the National Research Council of Canada. As a result of these contacts, several test approaches were identified. In addition to measuring the coach air flows at their real life speeds, other methods of air flow measurement and visualization which were considered include: measurement during an increased rate of air flow in order to decrease the sensitivity of the air speed measurements (perhaps five or ten times regular speeds); building a scale model and measuring air flows with a hot wire anemometer; and pumping water through a scale model and using dyes to observe flow distribution. Factors such as passenger occupancy, vehicle speed and use of the driver's air conditioning system may have a significant effect on the overall air distribution inside the coach. Such effects would likely be masked if artificially high flows were utilized and would be almost impossible to simulate using modelling techniques. Similarly, measurements taken on scale models would suffer from reduced accuracy and resolution. Consequently, the test program was limited to measuring the

air flows and patterns at their regular or typical operating conditions using actual vehicles.

To obtain a preliminary assessment of the air flow within a typical coach interior, a series of flow visualization and measurement tests was conducted. A number of flow visualization methods were investigated, including the use of a bubble generator and smoke pencils. The bubble generator method involved the use of helium, compressed air and a bubble solution to produce neutrally buoyant bubbles which could be used to trace air currents. However, it proved very difficult to obtain bubbles which were neutrally buoyant and for the coach application the method was prohibitively cumbersome. The smoke pencil method involved the use of standard air current tubes to generate a visible (low concentration) sulphuric acid aerosol which could be used to trace air currents. This method proved to be ideal for the coach application and was used for all flow visualization tests.

The preliminary flow visualization tests involved a comparison of air flow patterns inside the Prevost and MCI coaches for various test conditions. The test conditions included: stationary occupied and unoccupied coaches; unoccupied stationary and highway speed coaches; open driver's window at highway speeds; and operation of the driver's air conditioning system in unoccupied stationary and highway speed coaches. The preliminary flow measurement tests involved a comparison of the main air conditioning duct flow rates in three buses of the same model.

Although the results of the preliminary tests are discussed in more detail in Section 4.0, in summary it was found that there were only minor differences in the general air flow patterns between (stationary) occupied and unoccupied coaches and between (unoccupied) stationary and highway speed coaches. At highway speeds the open driver's window caused a change in the air flow patterns in the immediate vicinity of the driver, but the influence did not extend into the passenger compartment. The driver's air conditioning system also affected the air flow characteristics in the immediate vicinity of the driver and this influence did extend into the forward portion of the passenger compartment. The effect of the driver's

air conditioning system was similar for both the (unoccupied) stationary and highway speed tests. The preliminary flow visualization tests indicated that there were significant differences in the general air flow distribution patterns of the Prevost Marathon XL and MCI MC9 coaches due to the location of the ducting and return air ports. The preliminary flow measurement tests indicated that differences in the order of 12% existed in the duct flow rates for the three sample MC9 coaches.

Since the preliminary results indicated that the physical characteristics and the operating conditions of the coach air conditioning systems were more significant than vehicle speed and degree of occupancy on the air flow distribution characteristics, the next phase of the test program was to obtain a detailed air flow analysis on both the Prevost and MCI coaches.

As noted previously, there are numerous air conditioning controls and settings which can influence the coach air distribution. The air conditioning system controls for the MC9 and Marathon XL coaches are shown in Figures 1 and 2, respectively. During the preliminary test work, the effect of varying the system controls and settings was investigated. Generally, where a particular setting had a significant effect on the air flow characteristics (such as the damper setting in the fresh air make-up duct), the test program included measurements over the full range of possible settings. In other cases, all tests were conducted with a given control setting. For example, on the MC9 coach, the door exhaust damper was left fully open and the driver's system fresh air make-up left fully closed, since these settings correspond to the normal coach operating conditions. The passenger air conditioning system was always set on high and the temperature setting was turned to minimum during cooling cycles and maximum during heating cycles. This resulted in a maximization of temperature differences and a subsequent minimization of temperature measurement errors. Similarly, the driver's system was operated on high with appropriate minimum or maximum temperature settings.

The development of the required qualitative and quantitative tests is discussed in the following section under the appropriate headings. These tests include the illustration and measurement of air volume flow rates,

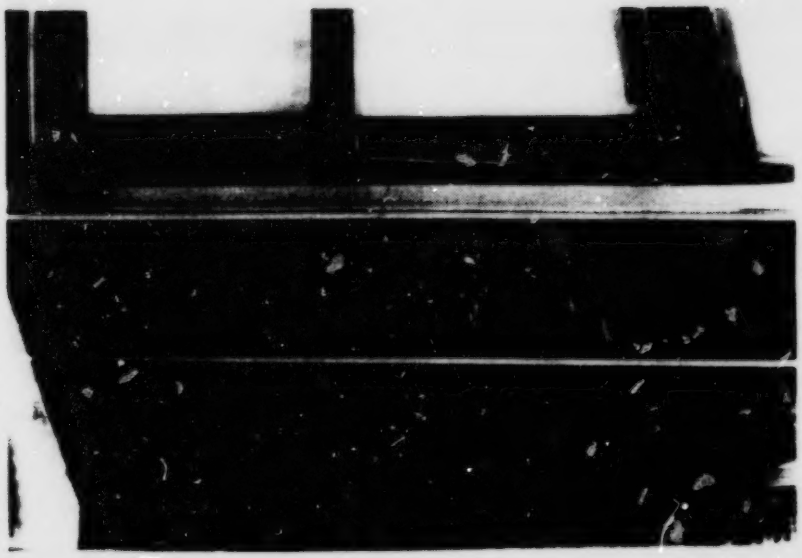

FIGURE 1 - Air Conditioning Controls - MC9

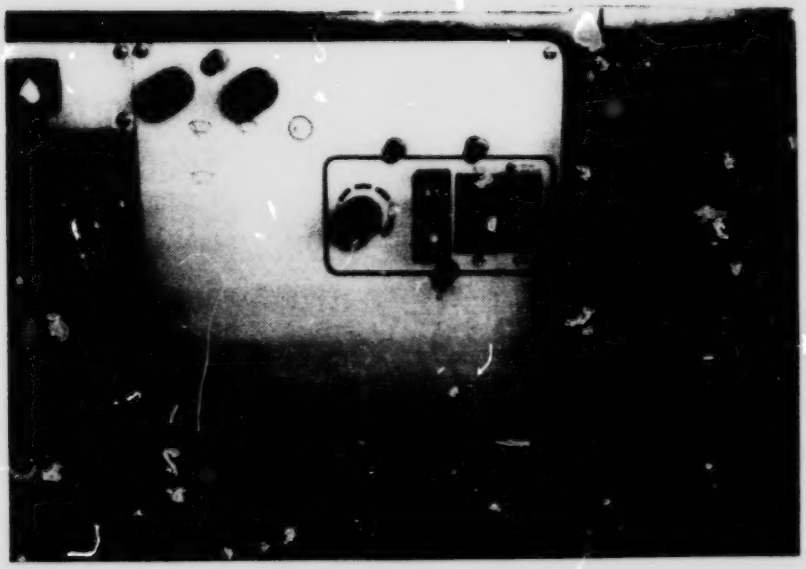

FIGURE 2 - Air Conditioning Controls - Marathon XL

air speed and direction at discreet locations, general air flow patterns within the coach, ventilation system balance, fresh air distribution and particle residence times.

Volume Flow Rates - To characterize the coach air flow distribution, the volume flow rates in the various air conditioning ducts are required. To develop procedures for measuring these volume flows and to select the necessary instrumentation for obtaining these measurements require an understanding of the air conditioning systems on the test coaches.

Figures 3 and 4 show air distribution system schematics for the MCI MC9 and Prevost Marathon XL, respectively. Similarly, Figures 5 and 6 show the plenum details for these coaches. From the figures it is evident that the two main differences in the coach air conditioning systems are the return air configurations and the intake vents for the fresh air make-up. The Prevost coach utilizes a single return air duct centrally located under a seat on the left hand side of the coach while the MCI coach uses multiple ports located in a wall plenum at the front and rear of the coach (see Figures 3 and 4). For fresh air supply, the Prevost coach uses a single intake duct and the MCI coach uses dual intake ducts (see Figures 5 and 6).

To measure the required flow rates on the test coaches (return air, conditioned air, etc.), the order of magnitude of each individual flow rate must be established so that appropriate instrumentation can be selected. Because of restricted accessibility to some of the coach ducting, special hoods or shrouds were constructed to obtain accurate flow rate measurements in certain cases.

In the passenger compartment, the flow rates of interest include: the fresh air intake, conditioned air, return air and exhaust air flow. In terms of air quality, the fresh air intake flow is probably the most significant of these. As shown in Figures 5 and 6, the MC9 has two identical fresh air intakes and the Marathon XL has a single larger fresh air intake. A metal shroud was constructed to fit both intake sizes and the shroud is shown in situ for the MC9 and Marathon XL in Figures 7 and

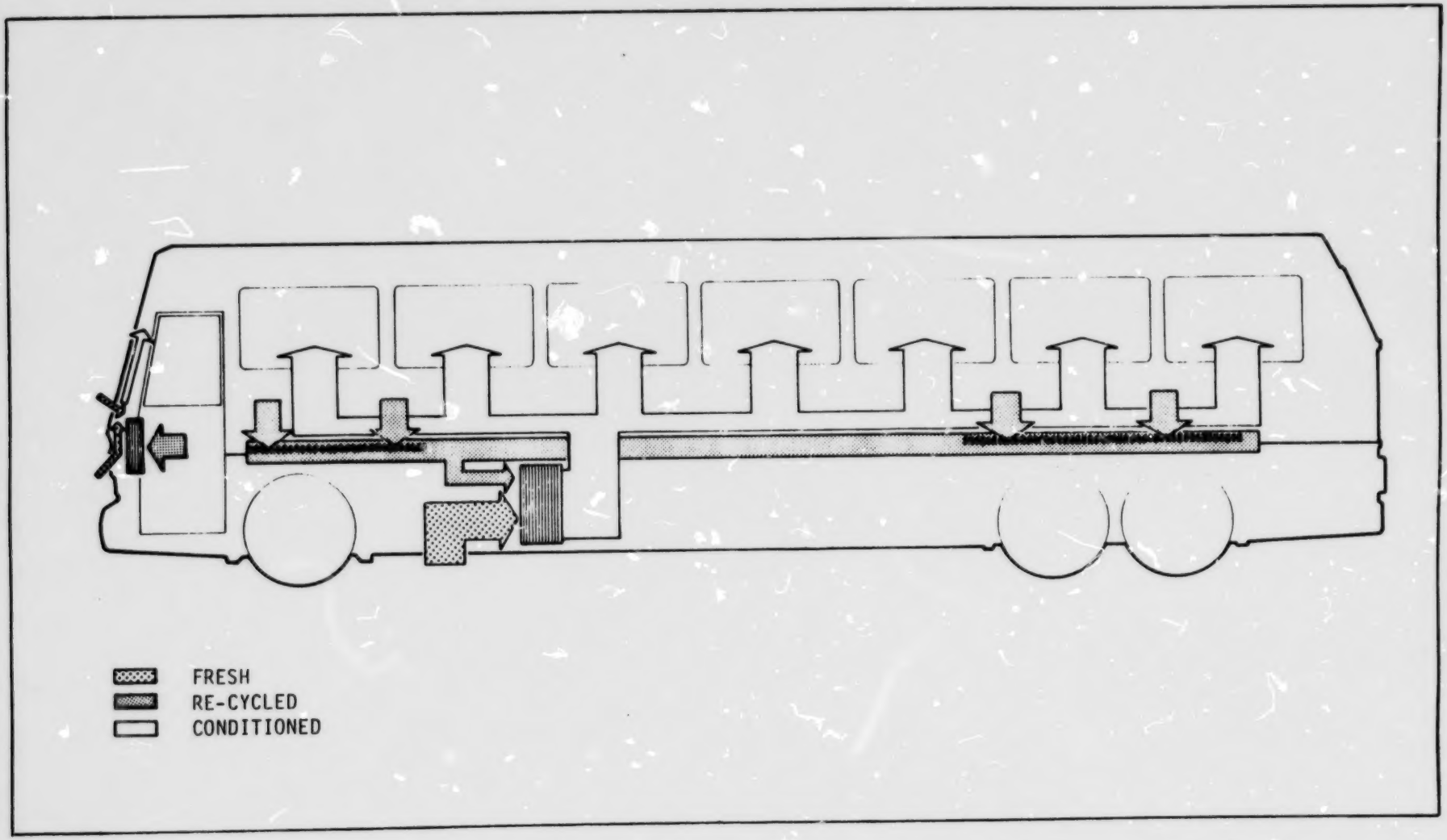

FIGURE 3 - Air Distribution Schematic - MC9

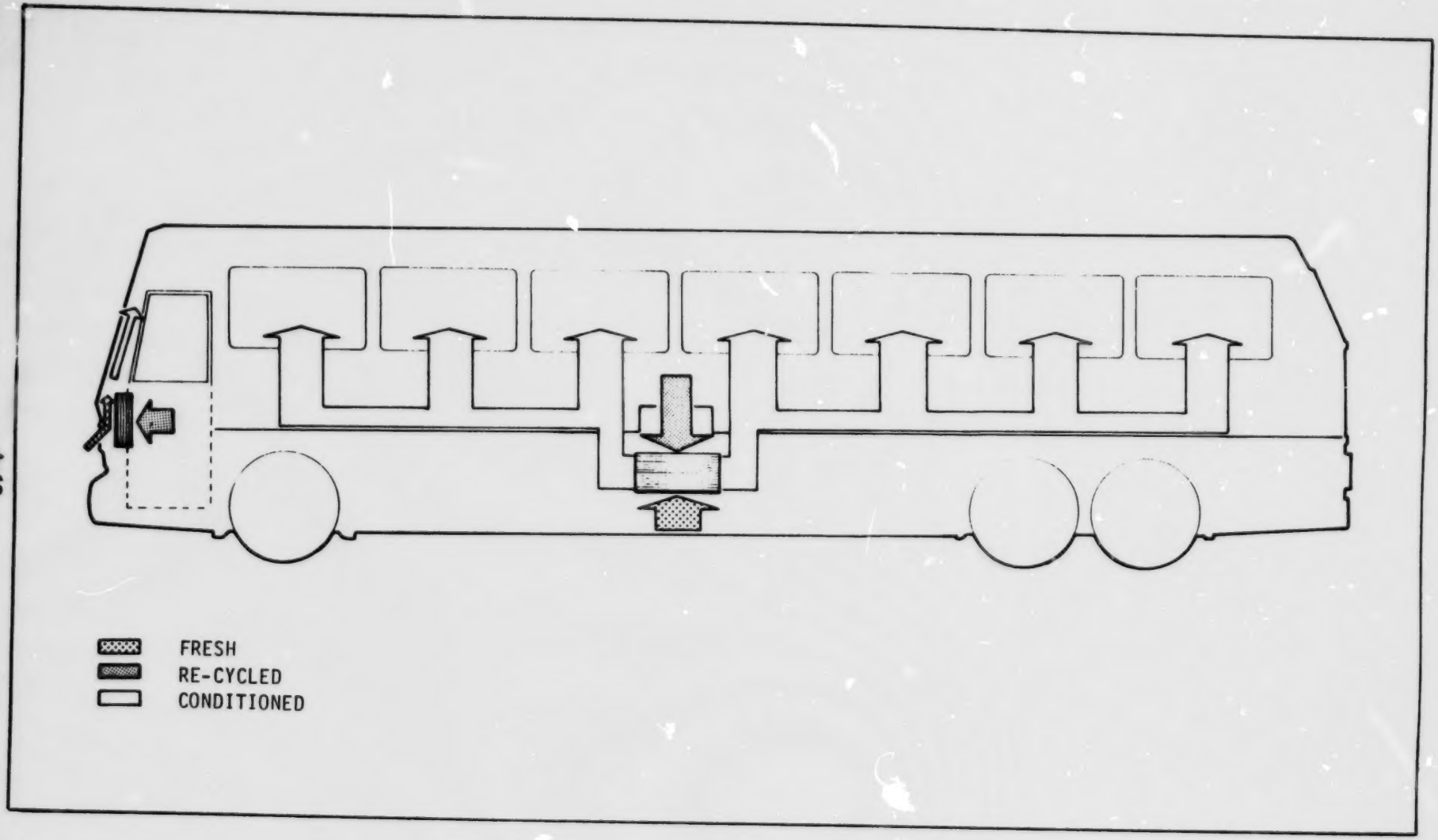

FIGURE 4 - Air Distribution Schematic - Marathon XL

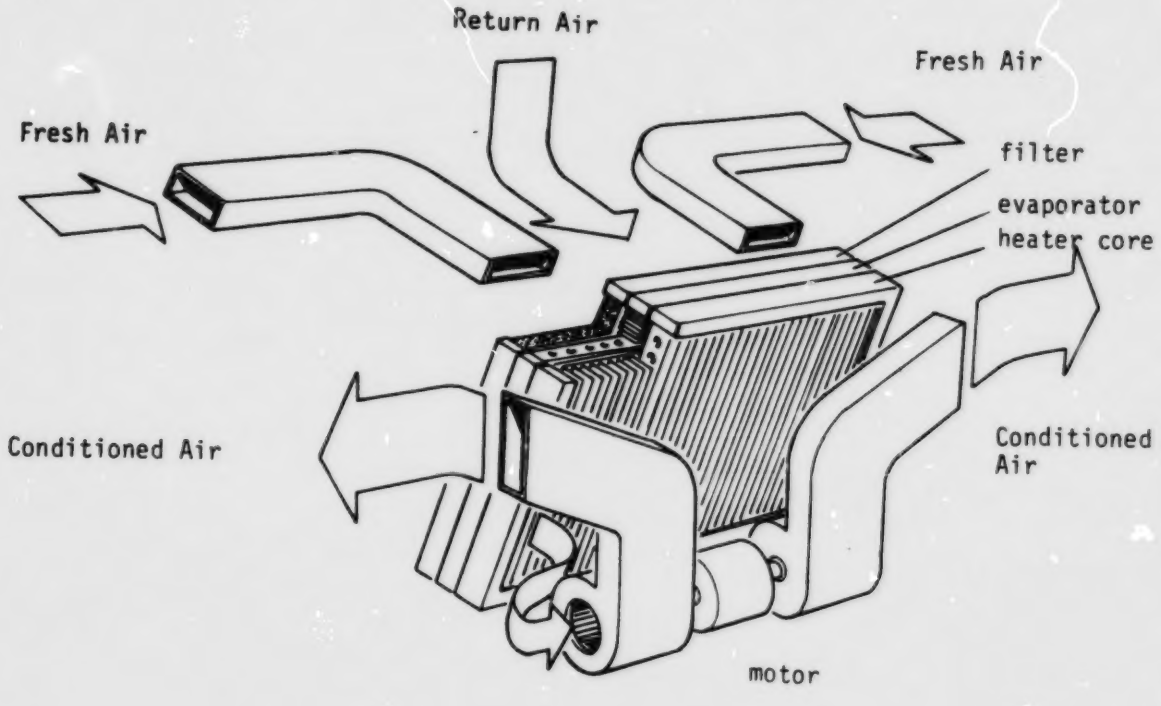

FIGURE 5 - Plenum Detail - MC9

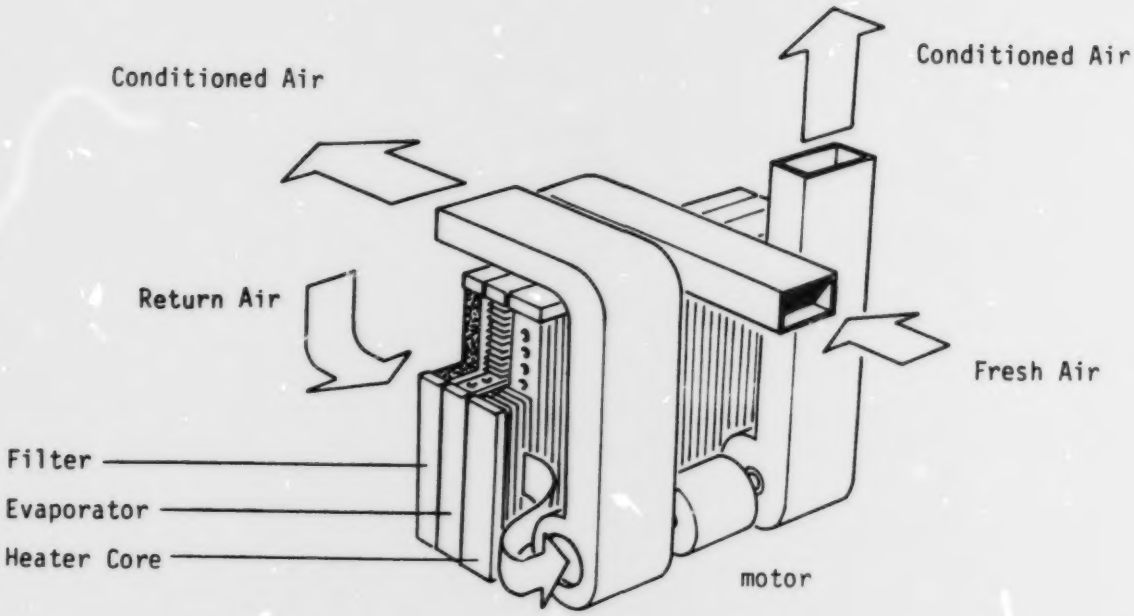

FIGURE 6 - Plenum Detail - Marathon XL

8, respectively. The intake flow rates were obtained by integrating the traversed velocity measurements obtained with a pitot tube and an electronic micromanometer. With this instrumentation set-up, depicted in Figures 7 and 8, flow rates in the order of 200 cfm were measured.

The MC9 utilizes a multiposition damper control in each fresh air intake duct to control the amount of fresh air admitted into the plenum. The fresh air damper controls are accessed from the forward baggage compartment. The Marathon XL uses a five position damper in the single fresh air intake duct to limit the amount of fresh air admitted into the plenum. The damper position can only be adjusted from the plenum (with the plenum access door open). For the test program, the fresh air intake flow was measured with the dampers in the fully open and fully closed positions to demonstrate the full range of the fresh air adjustment.

The conditioned air flow (fresh air plus return air) travels from the plenum through two separate ducts on both the MC9 and Marathon XL coaches, as shown in Figures 5 and 6. Each duct supplies conditioned air to one side of the coach. To measure the conditioned air flows, acrylic plenum doors were constructed which allowed a pitot tube to be traversed across the conditioned air ducts. These doors are shown in Figures 9 and 10 for the MC9 and Marathon XL, respectively. Flow rates in the order of 1400 cfm were measured with the pitot tube/micromanometer instrumentation. A typical measurement set-up in the conditioned air duct with the use of the pitot tube and micromanometer is illustrated in Figures 9 and 10. Figures 11 and 12 show the conditioned air ducts in the MC9 and Marathon XL, respectively, with the acrylic doors removed.

Measurement of the return air flow, the major component of the conditioned air flow, required different approaches for the MC9 and Marathon XL. The MC9 utilizes three sets of ports for the return air. Air is drawn from the front and rear of the passenger compartment through openings along the walls at floor level and through ports on either side of the ramped front aisle. The flow through the aisle return vents was found to be considerably stronger than the flow through the wall return vents and consequently, the pitot tube and micromanometer were used to measure the

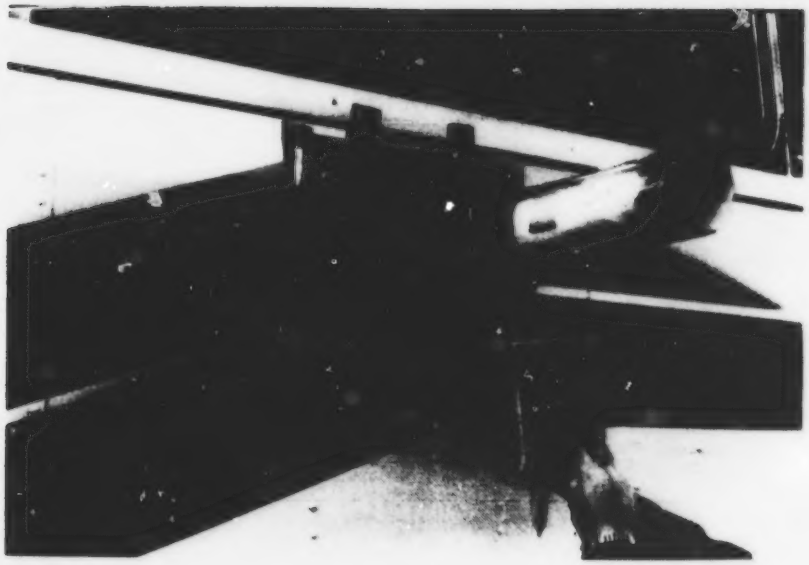

FIGURE 7 - Fresh Air Intake Shroud - MC9

FIGURE 8 - Fresh Air Intake Shroud - Marathon XL

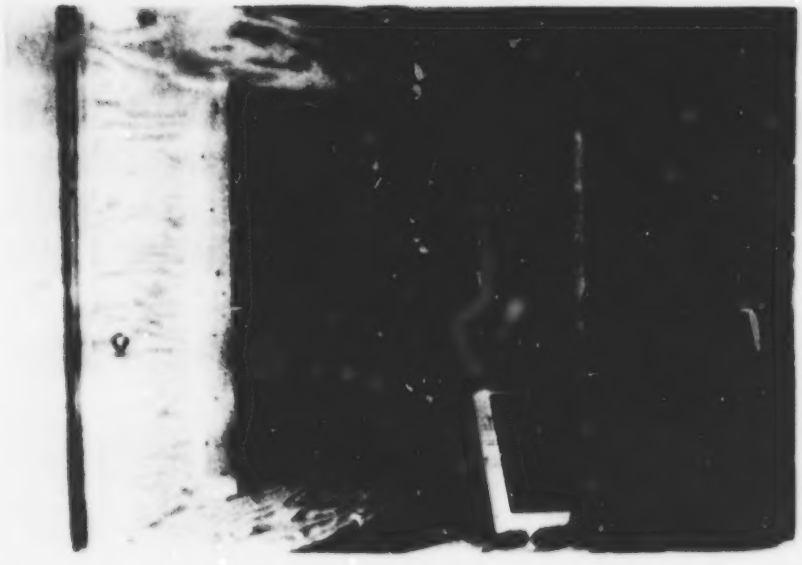

FIGURE 9 - Plenum Window - MC9

FIGURE 10 - Plenum Window - Marathon XL

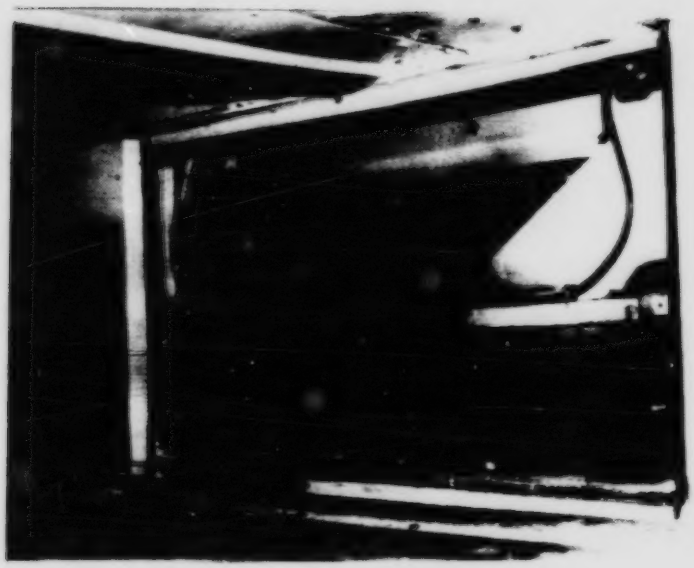

FIGURE 11 - Conditioned Air Ducts - MC9

FIGURE 12 - Conditioned Air Ducts - Marathon XL

aisle return flows and a hot wire anemometer (0-6000 fpm) was used to measure the side wall returns. To improve the measurement accuracy, temporary hoods were constructed to cover the returns, as shown in Figure 13. On the Marathon XL, a temporary hood was constructed to cover the single return air duct, as shown in Figure 14. With the relatively high flows through the single return air duct, the pitot tube and micromanometer instrumentation were used to measure the air velocities.

On both the MC9 and the Marathon XL, air is exhausted through the washroom holding tank to prevent odours from entering the passenger compartment. To measure these air flows, the pitot tube was traversed across the exhaust port and the readings were integrated over the exhaust port area to provide a total flow rate. On the MC9, an adjustable exhaust vent is also located in the main door. Exhaust flow rates on the door vent were measured in the full open mode since this is the standard operating condition. A shroud was used to measure the door exhaust flow, as shown in Figure 15. The linear velocities associated with the exhaust flow rate were in a transition range, and both the pitot tube and hot wire anemometer were used to obtain flow measurements.

The air flow rates of interest on the driver's air conditioning systems include the return air, the conditioned air blown out through the gasper and defroster vents and the fresh air intake. The MC9 and Marathon XL driver's systems are very similar, with the only major difference being the unconditioned fresh air gasper on the MC9.

On the MC9, the return air vent for the driver's system is quite large and, hence, the local air velocities are correspondingly small. This flow was measured using a low range hot wire anemometer (0-400 fpm), as shown in Figure 16. On the Marathon XL, the return air vent for the driver's system is relatively small, and this allowed the use of the shroud and pitot tube to obtain the flow measurements, as shown in Figure 17.

The defroster vent air flows were measured using the pitot tube and high range hot wire anemometer for both coaches, as shown in Figures 18 and 19. For the conditioned air gaspers, the pitot tube was used to traverse the

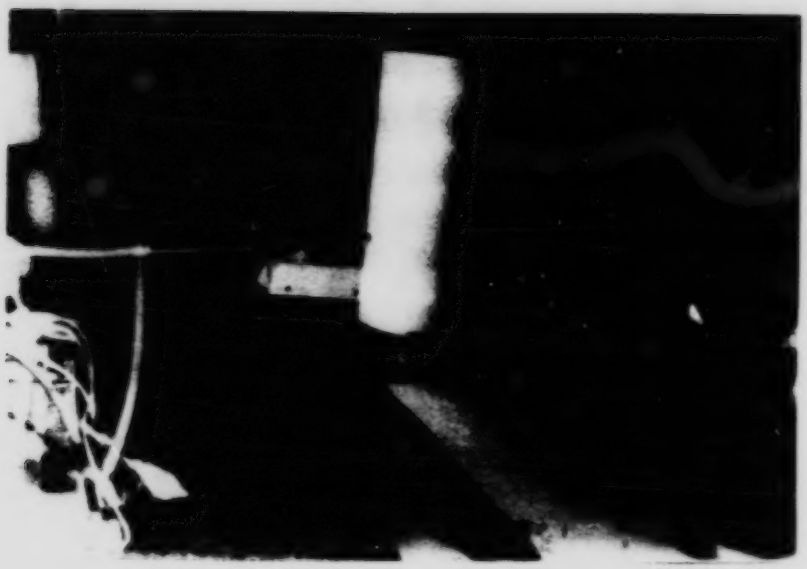

FIGURE 13 - Return Port Hood - MC9

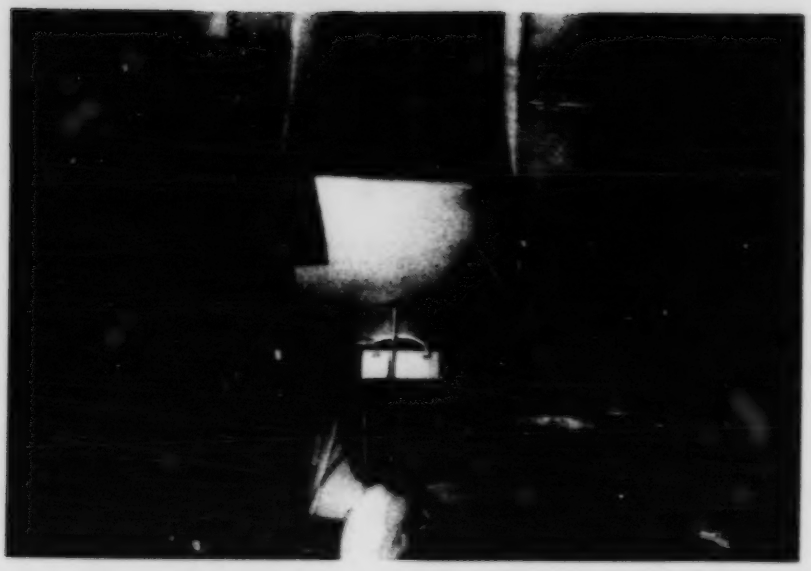

FIGURE 14 - Return Port Hood - Marathon XL

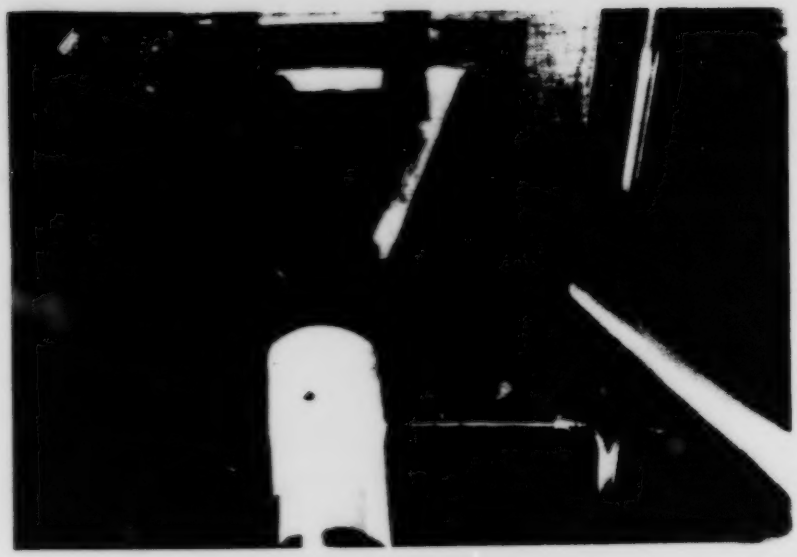

FIGURE 15 - Door Exhaust Shroud - MC9

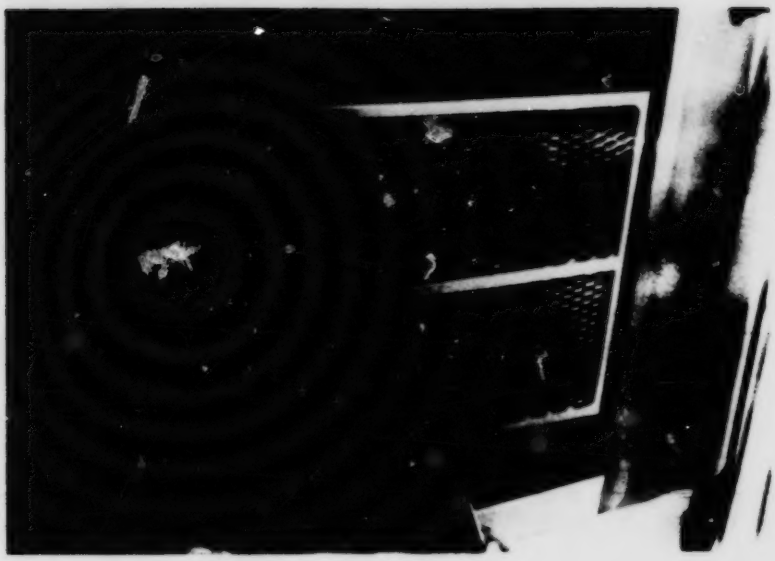

FIGURE 16 - Driver's Return Vent - MC9

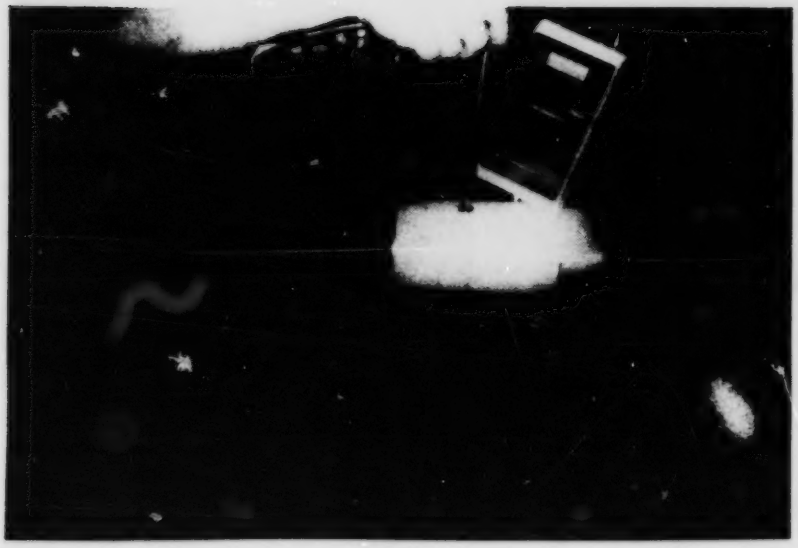

FIGURE 17 - Driver's Return Vent - Marathon XL

FIGURE 18 - Defroster Air Flow - MC9

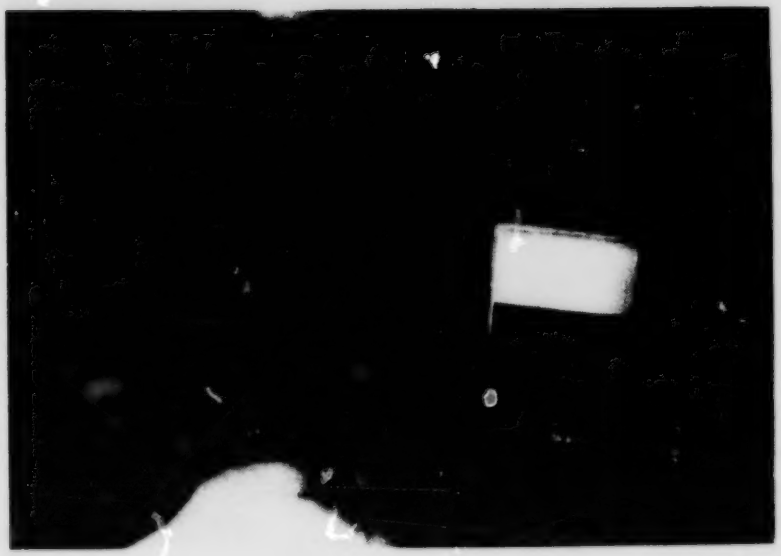

FIGURE 19 - Defroster Air Flow - Marathon XL

gasper outlet. For both coaches, the fresh air supply to the driver's system was operated in the fully closed position, as this is the standard operating condition.

Air Speed and Direction - In addition to quantifying the air volume flow rates into and out of the bus, local flow rates in the passenger compartment were obtained to determine whether the ambient conditions are in a comfortable range for the passengers. As discussed previously, the determination of flow direction was best accomplished using smoke pencils. To measure the magnitude of the flow, the low range hot wire anemometer was used.

The original approach to recording the air speeds and directions involved a Cartesian grid system in the coach interiors. An adjustable stand was constructed which allowed air speed and direction measurements to be taken at any (x, y, z) coordinate in the coach. A number of coach cross sections were tested with this arrangement, and although a large amount of data was generated, the data were not particularly useful in furthering an understanding of the coach air flow characteristics. This was due primarily to the large amount of information, and the difficulty of presenting the three dimensional air flow speeds and directions. Consequently, it was decided that air speed and direction measurements would be taken at the seat locations, at head and seat levels, since these air flows have the greatest influence on passenger comfort.

General Flow Patterns - To obtain the general flow patterns inside the coaches, smoke pencils were used to trace local flows, as described for the preliminary tests. Detailed air flow patterns were recorded graphically at various cross sections in the test coaches and, as noted previously, the preliminary tests included a comparison of occupied and unoccupied coaches and stationary and highway speed coaches. In addition to the detailed cross sectional sketches, overall flow sketches were produced to illustrate the relationship of the individual cross sectional flow sketches. To obtain the macro flow sketches, smoke bombs were used to introduce smoke into the coach fresh air intakes. This procedure illustrated a side to side and front to back distribution as well as the

overall flow tendencies. During the tests, smoke was channeled into the fresh air intakes using a shroud and flexible piping, as shown in Figures 20 and 21 for the MC9 and Marathon XL, respectively. On the MC9, which has two fresh air intakes, the smoke bomb tests were conducted separately on each intake and on both intakes at once. During each smoke bomb test, the smoke was observed in the plenum through the viewing door, as well as being monitored inside the bus.

Ventilation System Balance

To determine the efficiency of the ventilation system, the side to side and front to back air distribution in the coach was evaluated. A number of tests were conducted to check the ventilation system balance. As noted previously, the smoke bomb tests provide a qualitative indication of the system flow balance. To provide quantitative results, volume flow rates were measured in the conditioned air ducts to show side to side balance. Integrated air speed measurements along each air diffuser determine the front to back balance, as well as confirming the side to side balance. Finally, temperature measurements were recorded at flow measurement test points to confirm the findings of the other tests. For the air temperature tests, an array of thermocouples were installed along each air diffuser. During a series of ten minute tests, the thermocouples were monitored at ten second intervals using a Campbell Scientific 21X Micrologger, as shown in Figure 22.

For each ten minute air temperature test, the coach air conditioning system was operated in the cooling mode. By recording the consistency of the drop in the air temperature profiles along each diffuser, the ventilation system balance was determined.

Fresh Air Distribution - The most important component of the conditioned air flow to the passenger compartment is the fresh air content. Ideally, the fresh air should be evenly distributed throughout the conditioned air (well mixed) to provide equal quantities of fresh air for all coach passengers. Two tests will be used to qualitatively and quantitatively determine the fresh air distribution.

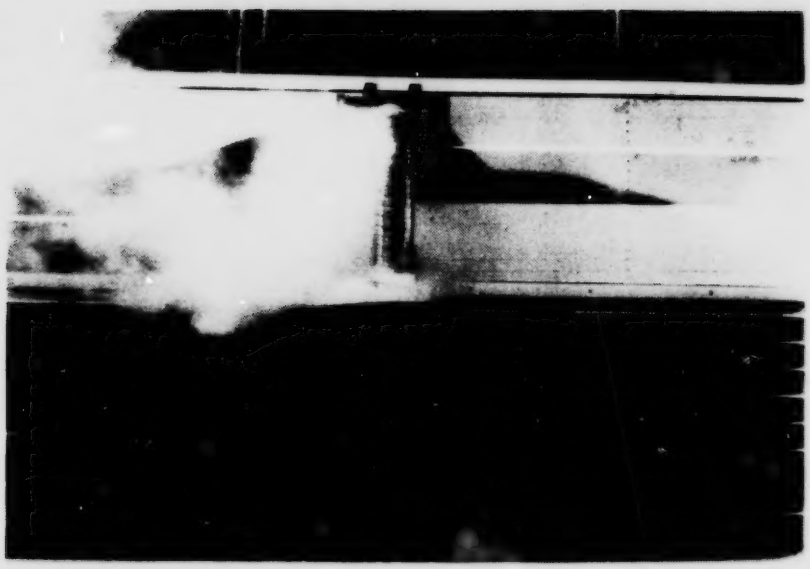

FIGURE 20 - Smoke Bomb Test - MC9

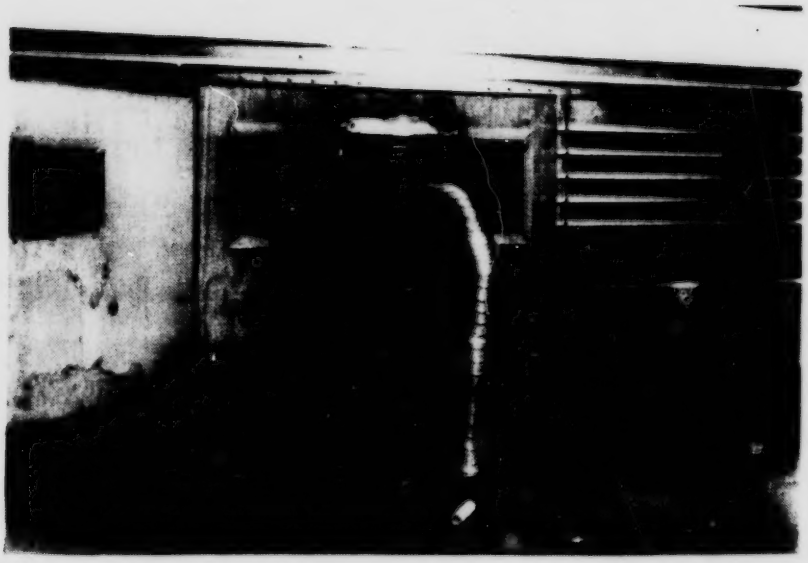

FIGURE 21 - Smoke Bomb Test - Marathon XL

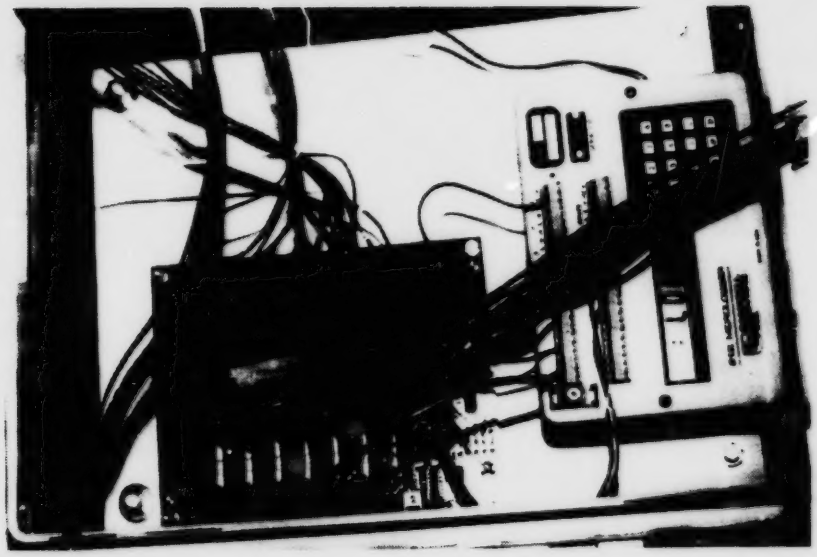

FIGURE 22 - Data Acquisition System Configuration

The qualitative test results were obtained by introducing smoke into the fresh air intakes. The fresh air distribution was observed by the fresh air component traced with the smoke. The fresh air distribution was observed at the diffuser outlets in the coach and the degree of mixing the plenum was observed through the plenum viewing doors.

The quantitative test involved using the air temperature ...ts described previously. With the coach circulating fans operating normally, but with no heating or cooling in the plenum, an external heat source was applied at the fresh air intakes. By measuring the temperature changes over time at the diffuser outlet, the fresh air distribution was determined, (ie. a temperature rise represents the heated fresh air entering the plenum). Figures 23 and 24 show the external heat source on the MC9 and Marathon XL coaches, respectively.

Particle Residence Times - One of the major passenger complaints on intercity buses is the presence of secondary or recirculated cigarette smoke. Thus, it is important to determine how long it takes pollutants in the coach to travel from their source to other areas in the coach, including the air conditioning system return air ducts. To measure pollutant flows, carbon dioxide was chosen as a tracer gas, since it is readily available and can be easily monitored using a manual sampler.

For measuring the pollutant flows inside the coaches, the critical path is from the pollutant source to the return air ducts, although the pollutant will be evenly distributed in the coach once it reaches the air conditioning system. Thus, during the tracer gas tests, the carbon dioxide concentration was measured in the conditioned air ducts (as ...n in Figures 25 and 26 for the MC9 and Marathon XL coaches, respectively,.

On the Marathon XL coach with the single return air duct, the tracer gas tests were conducted with the carbon dioxide source located in the front, centre and rear of the coach (one test for each source location). On the MC9 coach, which has a more complex return air system, the same three tests were conducted as for the Marathon XL coach. In addition, a fourth

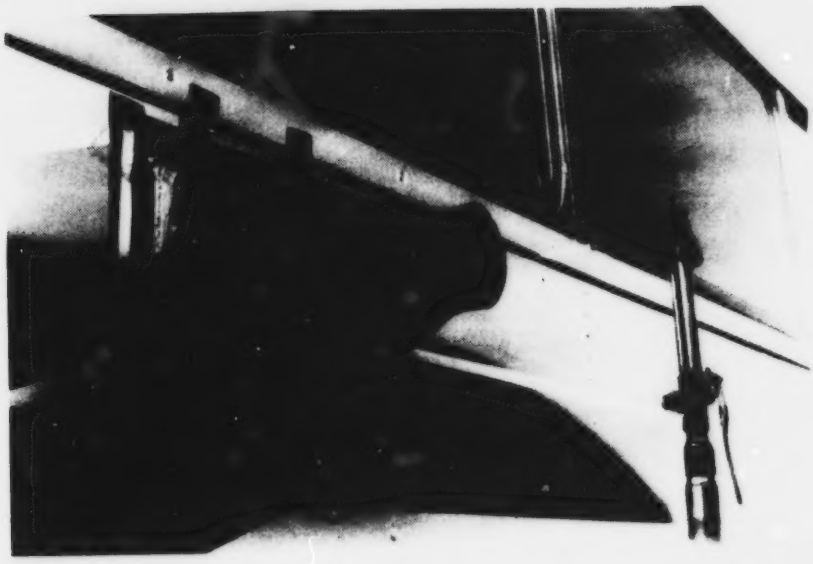

FIGURE 23 - External Heat Source - MC9

FIGURE 24 - External Heat Source - Marathon XL

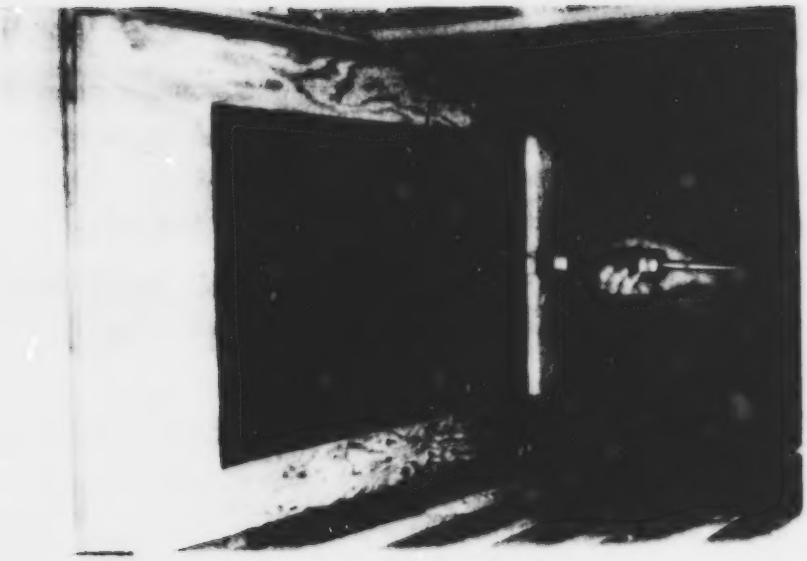

FIGURE 25 - Carbon Dioxide Monitoring - MC9

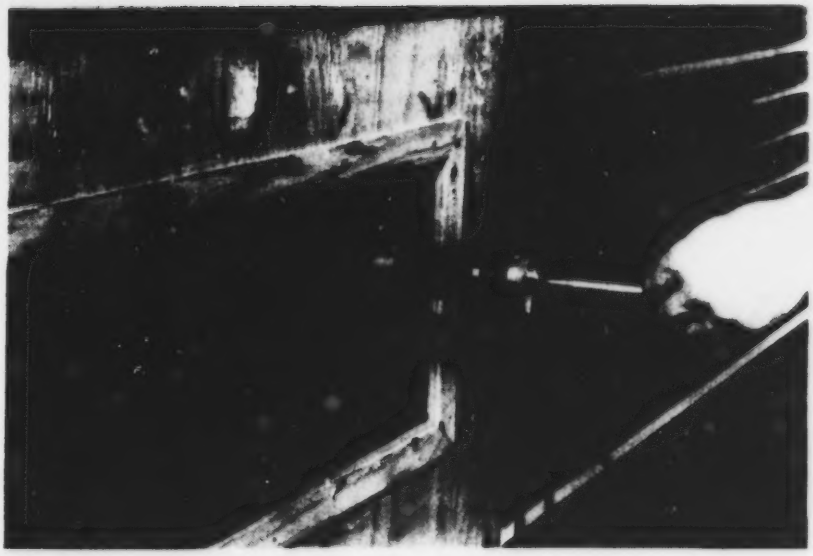

FIGURE 26 - Carbon Dioxide Monitoring - Marathon XL

test was conducted with the carbon dioxide source located in the rear of the coach. For this test, the carbon dioxide concentration was measured at the front of the coach, rather than in the conditioned air ducts. This provided an indication of the time required for the pollutants to reach the front return ports, as well as the rear ports, since pollutants from a source located in the rear of the coach travel to both the front and rear return air ports.

For each coach, a graph of the carbon dioxide concentration versus time (for a fixed flow rate pollutant source) was produced to illustrate the particle residence times.

3.0 TEST RESULTS

This section of the report presents the results of the test program described in the previous section.

3.1 Motor Coach Industries MC9

Appendix "A" contains the test results for the MCI MC9 coach. Tables A1 through A3 contain tabular data, Figures A1 through A12 contain flow diagrams and Figures A13 through A19 contain graphical results.

3.2 Prevost Marathon XL

Appendix "B" contains the tests results for the Prevost Marathon XL coach. Tables B1 through B3 contain tabular data, Figures B1 through B10 contain flow diagrams and Figures B11 through B17 contain graphical results.

4.0 DISCUSSION OF RESULTS

This section of the report presents a comprehensive discussion of the detailed test results, under the appropriate headings.

4.1 Volume Flow Rates

Tables A1 and B1 contain summaries of the volume flow rate measurements obtained on the test coaches. More detailed information is contained in Tables A2 and B2.

The total flow in the conditioned air ducts is almost identical for the two coaches, 2564 cfm and 2547 cfm for the MC9 and Marathon XL, respectively. In the MC9, the flow feeding the right hand side (RHS) of the coach was 1176 cfm and the flow feeding the left hand side (LHS) was 1388 cfm, a difference of about 17%. In the Marathon XL, the RHS flow was 1506 cfm and the LHS flow was 1041 cfm, a difference of about 37%. Although the measured total conditioned air flows were close to the manufacturer's specifications for both coaches, it is apparent that the duct flow balance could be improved.

For both test coaches, the fresh air intake flows were measured at both extremes of damper adjustment. For the MC9, the total fresh air intake flow was 33 cfm with the dampers in the closed position and 206 cfm with the dampers in the open position. These values represent 1.3% and 8.0% of the total conditioned air flow, respectively. For the Marathon XL, the fresh air intake flow varied from 201.9 cfm with the damper in position "one" (minimum flow), to 219.3 cfm with the damper in position "three" to 230.9 cfm with the damper in position "five" (maximum flow). These values represent 7.9%, 8.6% and 9.1% of the total conditioned air flow, respectively. It is apparent that the coach fresh air intake is always below 10% of the conditioned air flow, which is much lower than the 20% figure specified by the coach manufacturers. With maximum ventilation rates, the fresh air supply is in the range of 5 cfm to 6 cfm per seat. This ventilation rate is less than half of the commonly accepted standard of 15 cfm per person for building environments.

It is very likely that the low fresh air flow rates are a key reason for passenger complaints about poor air quality. This is particularly true for the MC9 coach, which is normally operated with the fresh air dampers fully closed (ie. fresh air intake of only 1.3% of the conditioned air flow).

The exhaust air flow rates measured for the two coaches were 86.9 cfm for the MC9 (door vent and washroom exhaust), and 68.8 cfm for the Marathon XL (washroom exhaust only). These figures represent 3.4% and 2.7% of the conditioned air flows, respectively. Since the air conditioning systems must be in a state of equilibrium, the exhaust flow rates must equal their respective intake flow rates. For the MC9 coach, the intake flow was 119.1 cfm (4.6% of the conditioned air flow) higher than the exhaust flow rate. For the Marathon XL, the intake flow was 150.5 cfm (5.9% of the conditioned air flow) higher than the exhaust flow rate. These differences are due to exhaust flows out of the coach which cannot be measured. Specifically, leakage occurs around the main door seal, the driver and washroom sliding window seals, the passenger compartment window seals and the emergency exit hatch seals.

Air flow measurements were taken in the passenger compartments of the coaches to provide an indication of the air conditioning system return air flow rates. For the MC9, the return air flow rate was 2256 cfm (88% of the conditioned air flow rate) and for the Marathon XL, the return air flow rate was 2221 cfm (87.2% of the conditioned air flow rate). Theoretically, the fresh air intake flow plus the return air flow equals the conditioned air flow. Any discrepancies in this identity are due to eit air leakage or measurement errors. The air flow measurement errors wer inimized by using highly accurate and properly ranged and calibrated instrumentation. For the MC9, the sum of the intake and return air flows was 2462 cfm, or 96% of the conditioned air flow. For the Marathon XL, the sum of the intake and return air flows was 2440 cfm, or 96% of the conditioned air flow. Therefore, the 4% discrepancy is largely attributed to the leakage in the system. Since the conditioned air side of the plenum is negatively pressurized, significant flow into the plenum can occur around the plenum access doors. In the MC9, this leakage flow

enters the plenum from the forward baggage compartment and in the Marathon XL, this leakage flow enters the plenum from outside the coach.

The return air vents on the MC9 exhibited unbalanced flow, as shown in Table A1. The return air vents on either side of the front aisle carry two thirds of the return air flow, with the remaining third being divided between the front and rear side wall return ports. In future, if electronic air filters are used to impede the degradation of air quality caused by second hand cigarette smoke, then care should be taken to locate the smoking section in the area of the coach which has the most direct return air route. In the MC9, this would be the front section of the coach whereas in the Marathon XL, this would be the central part over the single return air port.

Detailed air flow measurements for the driver's air conditioning system for both coaches are contained in Tables A2 and B2. Although the driver's air conditioning systems do not have a significant impact on the air quality of the coaches, flow measurements for the driver's systems are included for completeness. For the MC9, the air flow rate into the driver's system was 315.9 cfm and the total air flow out of the defroster and gasper vents was 268.3 cfm. In this case, the 16% difference between the measured inlet and outlet flow rates is likely due to measurement error, since the small size of the gasper and defroster vents made accurate flow measurements very difficult. For the Marathon XL, the air flow rate into the driver's system was 60.2 cfm and the total air flow out of the defroster vents was 281.1 cfm. For this coach, the measured inlet flow is unrealistically low. The most likely explanation for this anomalous figure is a damaged seal on the inlet grille, such that inlet air to the drivers air conditioning system is drawn from behind the vertical panel which the inlet grille is mounted on.

As described previously in the report, preliminary testing indicated that only minor differences in the coach air flow characteristics resulted from highway versus stationary measurements. As shown in Tables A2 and B2, sample measurements taken at highway speeds do not generally show significant differences from stationary measurements. However, one flow

increment worth noting is the door exhaust on the MC9. The door exhaust flow rate increased from 40.8 cfm (with the coach stationary) to 106.6 cfm (with the coach travelling at 90 km/h). This flow increase is due to the reduced pressure on the coach exterior caused by driving. Although the increase in the door exhaust flow rate is somewhat dependent on wind conditions, it should be noted that the increase of 65.8 cfm is only 2.6% of the total conditioned air flow and hence is not considered to be significant.

4.2 Air Speed and Direction

To determine whether the air speeds in the passenger compartment were within a reasonable comfort range, a number of air speed measurements were taken at passenger head and seat levels. To ensure that the flow measurement instrument was properly oriented during each measurement, smoke pencils were used to determine the air flow direction. The discreet air speed measurements obtained are shown in the sketches of Figures A2 through A4 and B2 through B5 for the MC9 and Marathon XL, respectively.

The generally accepted standard for a maximum comfortable air speed is 50 fpm. It can be seen from the specified figures that some of the local air speeds in both coaches exceed this standard by a large margin. Thus, air speed may be a contributing factor to the passenger air quality complaints being received by coach operators.

4.3 General Flow Patterns

Overall flow patterns were sketched for each coach and sketches were also produced at each seat cross section. Sketches for the MC9 coach are contained in Figures A1 through A12 and those for the Marathon XL coach are contained in Figures B1 through B10. The flow sketches are presented to provide a comprehensive representation of the general flow patterns inside each coach and to illustrate the effects on air flow patterns by factors such as passenger occupancy, coach speed and driver's air conditioning system operation.

Figure A1 shows the overall flow pattern inside the MC9 coach with the coach stationary and the driver's air conditioning system turned off. Although conditioned air enters the passenger compartment evenly through the diffusers along the window line, there is a strong forward flow tendency in the coach. This forward flow is caused by the strong pull of the front aisle return ports (through which two thirds of the return air flows), and by the flow leaving the coach through the door exhaust port. The forward flow in the coach is spiral in nature due to the vorticular flow caused by the conditioned air exiting the diffusers and by the staggered seat positioning. The numbers which appear in Figure A1 identify the local head and seat level air velocities in fpm.

Figure A2 shows a three dimensional sketch of the flow in the rear section of the MC9. The vorticular flow caused by air travelling from the diffusers, along the window and the bottom of the luggage racks, and down in the centre aisle, is clearly visible. Above the level of the luggage racks, there is a spiral flow towards the front of the coach. This flow is generally unimpeded, except on some coaches which have acrylic separators between the smoking and non-smoking sections. At the floor level, the downward air flow in the aisle separates and travels along the floor and up the wall, thus completing a circular pattern. Some of the flow along the floor is picked up by the return air ports located along the wall at floor level. It should be noted that the flow down the centre of the coach was roughly symmetrical about a vertical plane with a slight offset on either side due to the staggering of the seats. The numbers which appear in Figure A2 (and other figures) identify the local air velocities in fpm.

Figure A3 contains flow sketches for the MC9 at cross sections 2 through 8 (see Figure A1 for the cross section locations). A characteristic circular flow pattern is visible in all of the cross sections. At cross section 2, a lateral flow pattern along the floor to the wall return ports is visible, while in cross sections 3 through 7 this flow is directed upward along the wall. At cross sections 7 and 8, in the aisle at floor level, the beginning of a spiral air flow pattern is apparent. This vortex is caused by the return air vents on either side of the ramped

front aisle.

Figure A4 contains flow sketches for cross sections 9 and 10 with both the driver's air conditioning system off and on. At cross sections 9 and 10, with the driver's system off, a characteristic circular flow pattern is visible, as are the air flow patterns into the aisle return ports and the side wall return ports. With the driver's system on, there is substantial turbulence in cross section 10 (the first row of seats), but only a minimal effect is apparent at cross section 9. The air flow pattern at the other cross sections are not affected by the operation of the driver's air conditioning system.

Figure A5 shows the air flow directions at the diffuser exits. The conditioned air ducts expand into the wall plenums in the vicinity of cross section 8, and consequently, the air flows along the windows are angled forward in front of cross section 8 and rearward behind this cross section. These angled air flows have a minimal effect on the coach air flow patterns, since no major flow differences are apparent between the cross sections in front of and behind cross section 8.

Figure A6 depicts the overall flow pattern inside the MC9 coach with the coach travelling at highway speed (90 km/hr), with the driver's air conditioning system turned off, and with the driver's window open. With the driver's window closed, the coach interior air flow pattern at highway speed is identical to the stationary overall flow pattern (Figure A1). When the driver's window is open, air from inside the coach is drawn out through the window past the driver, as shown in Figure A6. This flow did not affect the air flow patterns in any of the passenger seats.

Figure A7 shows a three dimensional sketch of the flow in the rear of the MC9 (at highway speed). The flow patterns at highway speed are unchanged from the stationary flow patterns shown in Figure A2. Figure A8 contains flow sketches at cross sections 3 through 10. Comparing these sketches with those of Figures A3 and A4, the differences in the air flow patterns between stationary and highway speed conditions are negligible.

Figure A9 shows the overall flow pattern in the MC9 coach under stationary, occupied conditions. Figure A10 shows the rear section of the MC9 coach under the same conditions and sketches for cross sections 1 through 10 are shown in Figures A11 and A12. A comparison of Figures A1 through A4 with Figures A9 through A12 shows that the general air flow patterns in the coach were not altered significantly by the presence of passengers. However, one minor difference was noted. As shown in Figures A2 and A3, under unoccupied conditions there was a tendency for flow to move forward under the passenger seats. Under occupied conditions, this tendency was reduced due to the resistance caused by the passengers' legs.

Figure B1 shows the overall flow pattern in the Marathon XL coach under stationary conditions with the driver's system off. Since this coach utilizes a single return air port under the left hand seats at cross section 6 (see Figure B1), the general flow is from the front and rear of the coach towards the center. At the very front of the coach, there is a forward flow tendency in the upper portion of the passenger compartment and a rearward flow tendency in the lower portion of the passenger compartment. Also, in the first row of right hand seats, there is a flow tendency from the diffuser to the driver's window. This flow was very pronounced when the driver's window was open, but it also existed when the window was closed, indicating that some leakage occurred around the window seal. The numbers which appear in Figure B1 identify the local head and seat level air velocities in fpm.

Figure B2 shows a three dimensional sketch of the flow in the rear section of the Marathon XL. The characteristic circular air flow pattern is clearly visible in this sketch. Note the air flow through the wall vent into the washroom. On this coach, the washroom exhaust fan is the only exhaust port; all exhaust air from the coach passes through the washroom fan or leaks around window and door seals. The numbers which appear in Figure B2 (and other figures) show local air velocities in fpm.

Figure B3 shows flow sketches for cross sections 1 through 6 (see Figure B1 for cross section locations). In these cross sections, the symmetrical circular (spiral) flow patterns are visible, as is the forward tendency of

the flow along the floor and between the luggage racks. Towards the center of the coach (see cross sections 5 and 6), the flow becomes non-symmetrical as it converges on the return air port located on the left hand side of the coach.

Figures B4 and B5 show flow sketches for cross sections 7 through 11. It can be seen from these sketches that in the front portion of the coach, the air flow is towards the front in the upper portion of the passenger compartment, and towards the center of the coach along the floor of the passenger compartment. It is also apparent from these figures that the flow in the front portion of the Marathon XL coach is not symmetrical, due to a strong flow from the right side diffuser impinging on the left side of the coach. The reason for the non-symmetrical flow in this coach is the unbalanced right to left air distribution exiting the diffusers (as shown in Figures B11 and B12, which will be discussed in more detail in the following section of the report). Another consequence of the uneven flow distribution is an increase in turbulence (flow instability).

Figures B6 through B10 show overall and detailed flow sketches for the Marathon XL travelling at highway speed (90 km/hr). A comparison of these figures with Figures B1 through B5 show that there is virtually no difference in the air flow patterns between stationary and highway speed conditions.

Additional tests conducted on the Marathon XL indicated that the effect of passenger occupancy on the coach air flow characteristics was minimal. As noted for the MC9 coach, the only effect of passenger occupancy was a slight reduction in the air flow along the floor under the passenger seats. Tests were also conducted to determine the effect of the driver's air conditioning system on the passenger compartment air flow characteristics. The turbulence in the front of the coach caused by the unbalanced diffuser flows tended to mask the effects of the driver's air conditioning system, and consequently, there were no discernible differences in the passenger compartment air flow patterns with the driver's system on or off.

To summarize the overall air flow patterns in the two coaches, three dimensional flow sketches were produced. These sketches are shown in Figures 27 and 28 for the MC9 and Marathon XL, respectively.

4.4 Ventilation System Balance

The overall ventilation system balance can be an important factor in passenger comfort, since it determines the distribution of conditioned air to the passengers. The general left to right balance of the coach air conditioning systems can be determined by measuring the conditioned air flows in the main ducts. As noted previously, the flows in the conditioned air ducts of the MC9 coach were 1176 cfm to the right and 1388 cfm to the left, a difference of about 17%. For the Marathon XL coach, the flows were 1506 cfm to the right and 1041 cfm to the left, a difference of about 37%. While these figures provide a general indication of the left to right conditioned air balance, they do not provide any detailed information on the conditioned air distribution in the passenger compartment.

To determine the distribution of conditioned air entering the coach passenger compartments, velocity profiles at the diffuser outlets were constructed for each coach. Two velocity profiles for each side of each coach were produced, one profile for each of two elevations above the diffuser. These profiles are shown in Figures A13 and A14 for the MC9 coach and in Figures B11 and B12 for the Marathon XL coach. From these figures, it is apparent that there is a considerable amount of scatter in the data. This scatter is a consequence of the diffuser design. The diffuser consists of a series of square orifices such that the air flow along the diffuser is not continuous. Consequently, the profiles in Figures A13, A14, B11 and B12 should be used only as an approximate indicator of the longitudinal air flow distribution.

Figures A13 and A14 show that the conditioned air distribution on the MC9 is relatively uniform, both laterally and longitudinally. For the Marathon XL, however, the conditioned air distribution is very non-uniform, as shown in Figures B11 and B12. In this case, there is much

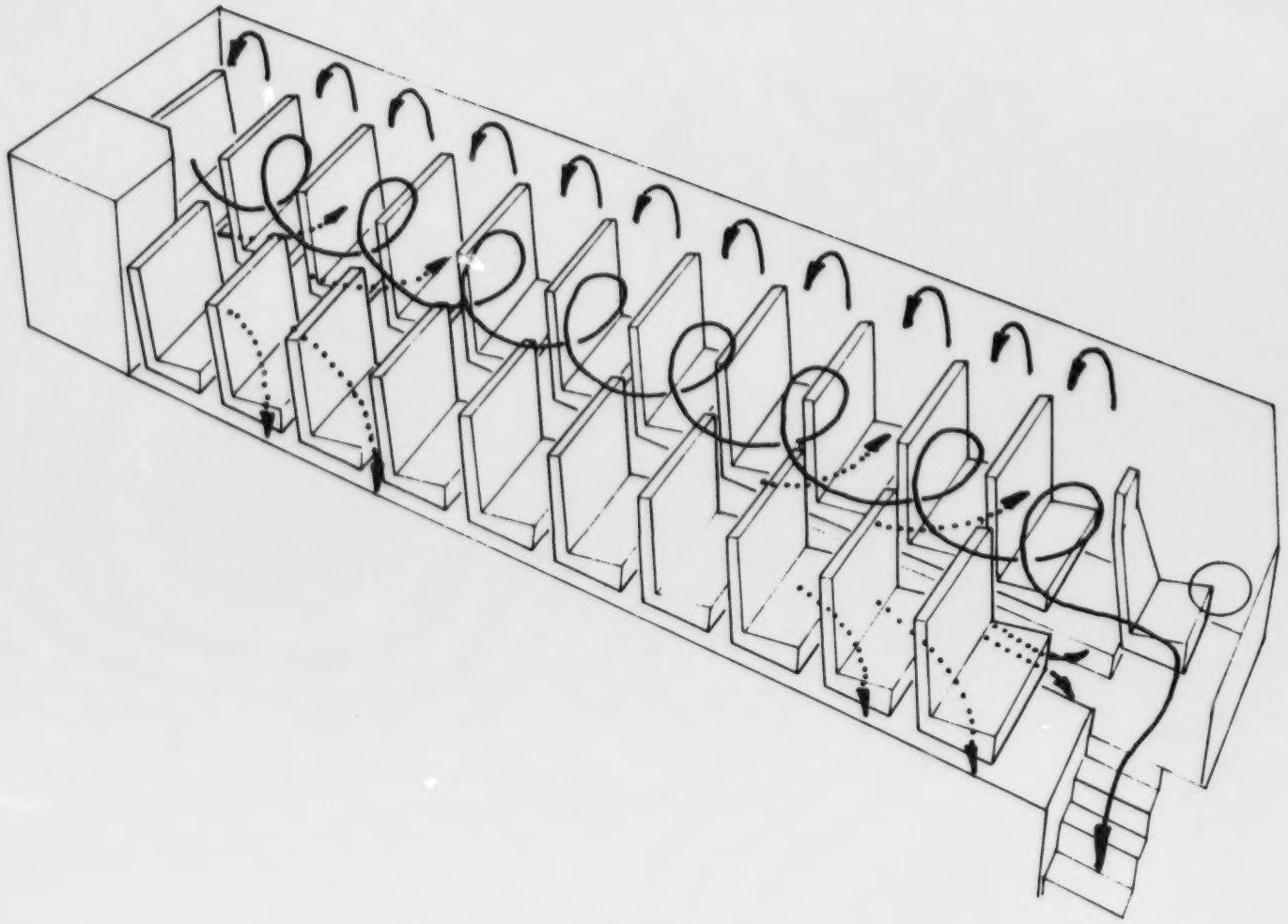

FIGURE 27

Overall Flow Sketch - MC9

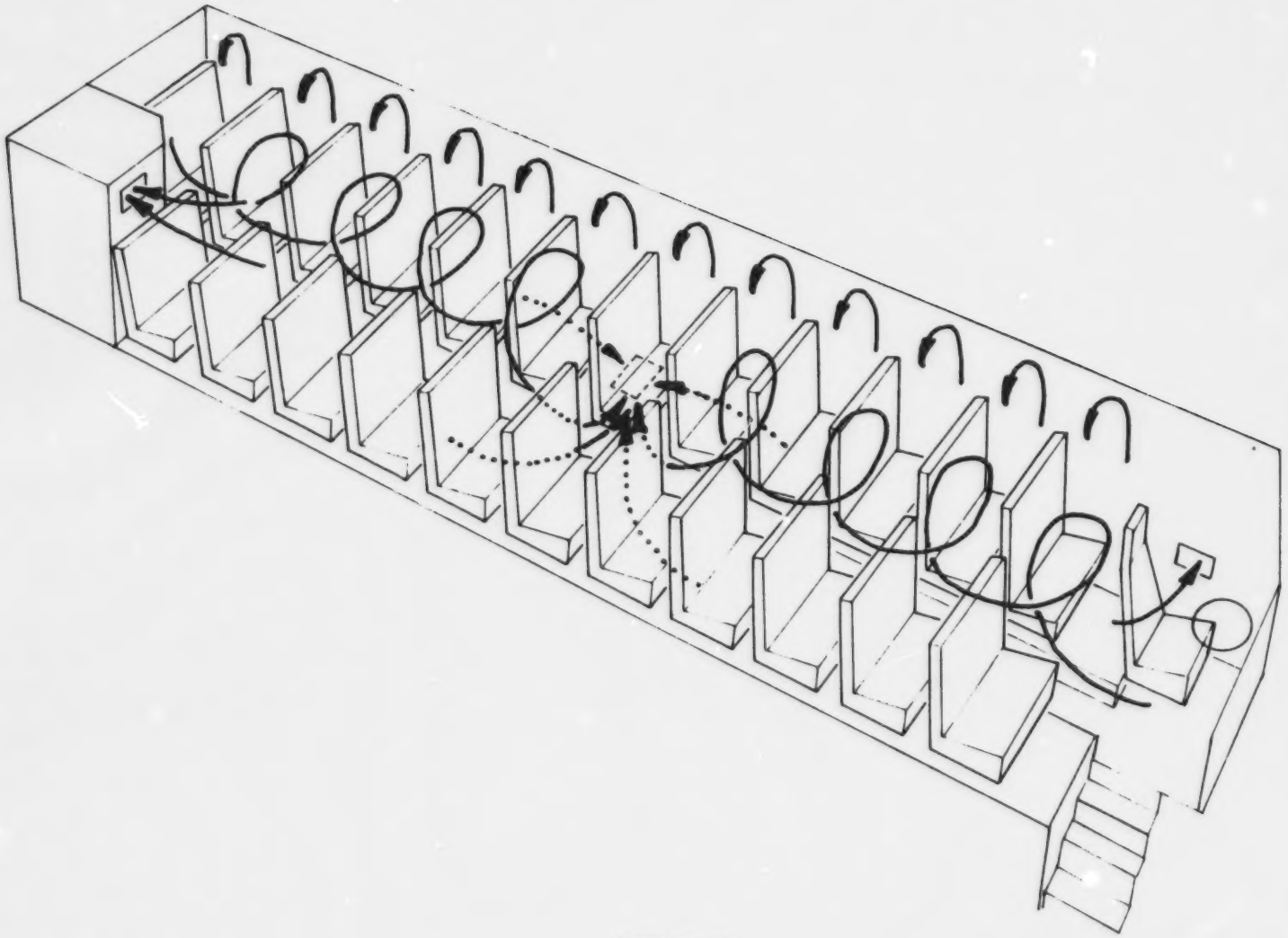

FIGURE 28

Overall Flow Sketch - Marathon XL

higher flow at the front and rear of the coach, relative to the center, as well as a considerable difference in the left to right flow balance. Although the non-uniformity of the conditioned air distribution is quite drastic, it should be noted that the coach passenger compartment is a very confined space and this will tend to mitigate the effects of the uneven air distribution. Another attenuating factor is the central location of the return air port. Since the overall flow in the coach is towards the center, the uneven longitudinal conditioned air distribution will tend to reduce flow short circuiting.

A modification kit is available from Prevost which can be used to increase the air flow to the center portion of the coach. The kit consists of a number of deflectors which are installed on each side of the coach to provide more uniform longitudinal air distribution (it should be noted that this modification will not affect the left to right flow balance in the coach). Details concerning the available modification kit are contained in Appendix "C".

Smoke bomb tests were conducted to provide additional qualitative information on the conditioned air distribution. Smoke introduced into each coach plenum via the fresh air intakes provided a method of visibly observing the conditioned air distribution in the passenger compartment. These tests showed a relatively even distribution on the MC9, while on the Marathon XL there was a definite right side flow bias with heavier front and rear smoke concentrations. Thus, the results of the smoke tests are in agreement with the measured velocity profiles.

Temperature tests were conducted to evaluate temperature uniformity at the diffuser outlets. For these tests, the passenger air conditioning systems were operated in the cooling mode for a period of ten minutes, with temperature profiles being automatically monitored every ten seconds. Temperature profiles were plotted for each side of each coach at times of zero, one, two, five and ten minutes into the test. For the MC9 coach, the right and left temperature profiles are shown in Figures A15 and A16. For the Marathon XL, the right and left temperature profiles are shown in Figures B13 and B14.

As shown in Figures A15 and A16, the temperature profiles for the MC9 are very uniform during the cooling cycle. This indicates that full mixing of the cooled air is occurring in the plenum and that this air is being evenly distributed in the passenger compartment. As shown in Figures B13 and B14, the temperature profiles for the Marathon XL are not completely uniform. At the end of the cooling cycle, the air temperature in the central part of the coach is higher than the air temperatures in the front and rear. These temperature profiles are a direct consequence of the air velocity profiles (as shown in Figures B11 and B12). It should be noted that the last thermocouple on the right side of the coach is located in the washroom where no diffuser exists, and consequently, this thermocouple experienced a minimal temperature drop during the cooling cycle.

4.5 Fresh Air Distribution

The previous section described the conditioned air distribution in the test coaches. In addition to knowing the conditioned air distribution, it is important to know how the fresh air component of the conditioned air is distributed. This can be determined relatively easily by establishing the degree of fresh air mixing in the air conditioning system plenum.

During the smoke bomb tests, smoke was introduced into the air conditioning plenum through the fresh air intake ducts. Thus, the smoke represented the fresh air component of the conditioned air. During each test, the smoke concentration was observed in the passenger compartment and in the plenum (through the acrylic viewing door).

For the MC9 coach, three smoke bomb tests were conducted. These tests involved introducing smoke into the left and right fresh air intakes both separately and simultaneously. The results of the three tests were identical in that full mixing occurred in the plenum and smoke concentrations in the passenger compartment were correspondingly uniform. Thus, with full mixing in the plenum, the fresh air distribution in the passenger compartment is identical to the conditioned air distribution, which is relatively uniform in the MC9 coach.

For the Marathon XL coach, a single smoke bomb test was conducted since this coach utilizes a single fresh air intake port. The smoke mixed fully in the plenum, such that the fresh air component was evenly distributed in the conditioned air. Thus, the fresh air distribution in the passenger compartment is identical to the conditioned air distribution, which is non-uniform in the marathon XL coach. This was confirmed by observing the smoke concentrations in the passenger compartment which closely paralleled the measured velocity profiles.

To quantify the smoke test results, temperature tests were conducted using the thermocouple arrangement previously described. With an external heat source applied at the fresh air intake, the fresh air component of the conditioned air was at a much higher temperature than the return air component. Thus, by measuring air temperatures at the diffuser outlet, the fresh air distribution in the passenger compartment was determined. As with the smoke tests, three temperature tests were conducted on the MC9 and one temperature test was conducted on the Marathon XL. During each test, temperature profiles were measured over a period of ten minutes.

Figures A17 and A18 show temperature profiles for the right and left sides of the MC coach, with the heat source being applied at the left side fresh air intake. From Figure A17, it can be seen that the right side temperature profiles show a consistent temperature increase, with the individual temperature profiles being very uniform (with the exception of the thermocouple located in the washroom). On the left side, as shown in Figure A18, the temperature profiles show a consistent temperature increase, but the individual temperature profiles are not as uniform as those on the right side. The reason for the higher temperatures at a longitudinal distance of 44 inches on the left side, is that conduction and convection cause a local temperature increase at the point of application of the heat source (the fresh air intake ports on the MC9 are located just below the window line). Thus, the temperature measurements confirm that the fresh air component of the conditioned air is distributed evenly in the MC9 coach. The remaining two temperature tests (with the heat source located at the right side fresh air intake and with a heat

source located at both of the fresh air intakes), provided the same results as the first test. In both cases, the temperature profiles showed consistent increases and the individual temperature profiles were quite uniform with the exception of localized temperature increases at the point (or points) of heat application.

Figures B15 and B16 show temperature profiles for the right and left sides of the Marathon XL coach, with the heat source being applied at the single left side fresh air intake. It can be seen from these figures that the heating profiles closely parallel the measured velocity profiles. The overall temperature rise on the right side of the coach was substantially higher than on the left side, due to the higher right side conditioned air flow. Similarly, on both the right and left sides of the coach, the temperature rise in the central section of the coach is lower than in the front and rear sections, due to the reduced conditioned air flows in the center. The temperature profiles shown in Figures B15 and B16 show that the fresh air distribution is the same as the conditioned air distribution, indicating that full mixing of fresh air and return air occurs in the plenum.

4.6 Particle Residence Times

To determine particle residence times, carbon dioxide tracer gas tests were conducted. For each of the tests (four on the MC9 coach and three on the Marathon XL coach), the carbon dioxide source was set at 35 standard cubic feet per hour.

For the MC9 coach, three of the tests involved measuring the carbon dioxide concentrations in the conditioned air ducts with the source located at the front, middle and rear of the coach passenger compartment. An additional test was conducted with the carbon dioxide concentration being measured at the front of the passenger compartment while the source was located in the rear of the coach. The results of the four tests are shown in Figure A19. It can be seen from this figure that the carbon dioxide concentration in the conditioned air increased most rapidly with the source located in the front of the coach. This is due to the strong

pull of the front return air ports. With the source located in the middle of the coach, the measured carbon dioxide concentration experienced a time lag (of about two minutes), since the tracer gas had to travel from the middle of the coach to the front return air ports.

With the source located in the rear of the coach, the carbon dioxide concentration is initially higher than for the center position, with a cross over occurring at a time of about six minutes. The initial higher concentration is due to carbon dioxide entering the rear return air ports and getting into the air conditioning system quite quickly. However, most of the tracer gas travels through the entire coach and enters the air conditioning system via the front return ports. Since most of the gas must travel through the entire coach, this source location provides the longest time lag of the three positions.

With the source located at the rear of the coach and with the carbon dioxide concentration measurements being taken at the front of the coach, the greatest time lag was observed (about four minutes difference compared with the source located at the front). This provides an indication of the time required for the tracer gas to travel the length of the coach, since the tracer gas entering the rear return ports is not measured.

The results of the four tests indicate that for a pollutant source located anywhere in the coach, most or all of the pollutant would travel through the coach to the front return air ports. Once the pollutant enters the air conditioning system, it is distributed throughout the coach. For any pollutant source location, a steady state situation is reached after about 25 minutes, with time lags of up to four minutes caused by varying the source location. This suggests that cigarette smoking passengers should be located in the front of the coach, provided that the cigarette smoke can be filtered out of the return air or conditioned air before it is returned to the passenger compartment.

For the Marathon XL coach, the carbon dioxide concentration was measured in the conditioned air ducts with the carbon dioxide source located at the front, middle and rear of the coach passenger compartment. The results of

the three tests are shown in Figure B17. The fastest rise in tracer gas concentration occurred for the source located in the centre of the coach, since this is where the single return air port is located. With the source located in the rear of the coach, a time lag of between one and two minutes occurred, due to the tracer gas travelling from the rear of the coach to the central return air port. For the test with the source located in the front of the coach, a problem was encountered with the carbon dioxide regulator. After setting the source at 35 standard cubic feet per hour, freezing of the regulator a few minutes into the test caused the flow to drop and consequently, the steady state gas concentration for this test was lower than for the other two tests. However, in the initial part of the test, the measured concentrations were almost identical to the values measured for the source in the rear location. This indicates that the time lag is the same for the front and rear source locations, which is as expected, since the return air port is located in the centre of the coach.

The results of the three tests indicate that for a pollutant source located anywhere in the coach, all of the pollutant would travel to the central return air port. Once the pollutant enters the air conditioning system, it is distributed throughout the coach. For any pollutant source location, a steady state situation is reached after about 16 minutes, with a time lag of between one and two minutes caused by varying the source location. This suggests that cigarette smoking passengers should be located in the centre of the coach, provided that the cigarette smoke can be filtered out of the return air or conditioned air before it is returned to the passenger compartment.

5.0 CONCLUSIONS

Based on the contents of this report, the following conclusions can be made:

1. On both the MCI MC9 and the Prevost Marathon XL, the fresh air volume flow rate was less than 10% of the total conditioned air flow, compared to the specified value of 20%.

2. The fresh air intake on the MC9 coach is adjustable between 1.3% and 8.0% of the conditioned air flow. Under normal operating conditions, the fresh air damper is fully closed, such that the fresh air intake is only 1.3% of the conditioned air flow.

3. The fresh air intake on the Marathon XL coach is adjustable between 7.9% and 9.1% of the conditioned air flow. Thus, the five damper settings on the fresh air intake have the capacity to vary the fresh air supply by only 1.2% of the conditioned air flow.

4. The measured exhaust air flow on both of the coaches was below 4% of the conditioned air flow. This means that more than half of the exhaust flow for both coaches is due to leakage around various window, door and other seals.

5. Highway speed operation introduced only minor changes in the flow rates and flow patterns of the two coaches.

6. Tests conducted with passengers demonstrated that the flow characteristics of an occupied coach were almost identical to those of an unoccupied coach.

7. It was observed that the differences in flow characteristics between stationary versus highway speed conditions and occupied versus unoccupied conditions were of the same order of magnitude as the flow differences between various coaches of the same model.

8. The conditioned air flow patterns were found to be uniform and symmetrical in the MC9 coach. In the Marathon XL coach, a stronger flow existed on the right side of the coach and the longitudinal distribution of air from the diffusers was not uniform.

9. In the MC9 coach, the front aisle return ducts accounted for 67% of the total return flow and the front aisle and wall return ducts together accounted for 81% of the total return flow.

10. The general air flow patterns in the MC9 coach indicate an overall forward flow tendency (towards the door exhaust port and the front return ports). The general air flow patterns in the Marathon XL indicate a general flow towards the centre of the coach (where the single return air port is located).

11. The fresh air is evenly mixed with the return air in both coaches and consequently, the fresh air distribution follows the same pattern as the conditioned air distribution.

12. The driver's air conditioning system had only a minor effect on the overall flow characteristics for both of the coaches. This consisted of an increase in turbulence in the front portion of the passenger compartment.

6.0 RECOMMENDATIONS

Based on the contents of this report, the following recommendations can be made:

1. The fresh air intake control damper should be set to the full open position on all coaches in order to maximize the fresh air input.

2. The adjustable exhaust vent in the door of the MC9 coach should be set to the full open position to maximize stale air exhaust.

3. Measures should be taken to increase the intake and exhaust air flows on both coach models. Intake and exhaust flow rates of 20% of the current conditioned air flows should be used, provided that this does not tax the existing coach heating and cooling capacities.

4. In new coaches, measures should be taken to reduce air flow velocities in the vicinity of passengers. This could be accomplished by reducing the total conditioned air flow or by altering the design of the diffusers and/or the coach interiors.

5. If smoking is to be permitted during intercity travel, special filters or cleaners should be installed to prevent the distribution of pollutants to all coach passengers. In addition, the smoking section should be located at the front of the MC9 coach and in the center of the Marathon XL coach, to minimize the effect of pollutants on non-smoking passengers.

6. On the Marathon XL coaches which have uneven longitudinal ventilation, the Prevost ventilation duct improvement kit can be installed to attenuate the longitudinal air flow distribution. However, qualitative tests conducted on two modified coaches indicate that the kit results in only marginal air flow distribution improvements.

ANNEX A

Test Results: Motor Coach Industries MC9

ANNEX A

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DATA TABLES

Volume flow measurement locations	Component volume flows (ft^3/min)	Percentage of the total volume flow (%)
A. Driver's system		
Recycled supply		
(high)	268.4	
B. Passenger		
Compartment		
1. Conditioned air ducts	(R) 1176	45.9
	(L) 1388	54.1
	2564	100.0
2. Fresh air intakes		
(i) Open	206	8.0
(ii) Closed	33.0	1.3
3. Exhaust vents	86.9	3.4
4. Leakage		4.6
5. Recycled vents		
(i) rear side	431	16.8
(ii) front side	309	12.1
(iii) front aisle	1516	59.1
	2256	88.0

TABLE A1

Volume Flow Rate Summary

Volume flow measurement location	Stationary			Highway speed (90 km)		% Difference between volume flow rates (%)
	Cross Sectional Area (ft^2)	Integrated air speed (ft/min)	Volume flow rate (ft^3/min)	Integrated air speed (ft/min)	Volume flow rate (ft^3/min)	
A. Driver's system						
1. Into evaporator	1.4320	220.6	315.9	161.3	231.0	-26.9
2. Out of gasper	0.0085	3271	27.8	-	-	
3. Out of defroster	(i) 0.0316	(R) 3626	114.5	(R) 2933	92.6	-19.1
		(L) 3429	108.4	(L) 2733	86.3	-20.3
	(ii) 0.0037	(R) 2680	9.9	(R) 2100	7.8	-21.6
		(L) 2069	7.7	(L) 1800	6.7	-13.0
B. Passenger Compartment						
1. Conditioned air ducts	0.3056	(R) 3847	1176	-	-	
		(L) 4542	1388			
2. Fresh air intakes						
(i) open	0.0985	(R) 1050	103.4	-	-	
		(L) 1042	102.6			
(ii) closed	0.0985	(R) 35	3.4	-	-	
		(L) 300	29.6			
3. Door exhaust	0.0985	413.8	40.8	1082	106.6	+161.3
4. Washroom exhaust	0.0197	2341	46.1	-	-	
5. Recycled air vents						
(i) front side	0.2290	(R) 695.0	159.2	(R) 709.7	162.5	+2.1
	0.3220	(L) 466.4	150.2	-	-	
(ii) rear side	0.6220	(R) 327.7	203.8	(R) 329.9	205.2	+0.7
	0.7147	(L) 318.2	227.4	-	-	
(iii) front aisle						
right	(i) 0.1015	1517	153.9			
	(ii) 0.1238	1397	172.9			
	(iii) 0.1462	925	135.2	-	-	
	(iv) 0.1697	990	168.0			
	(v) 0.1931	611	118.0			
left	(i) 0.1015	1674	169.9	1721	174.7	
	(ii) 0.1238	1517	187.8	1443	178.6	
	(iii) 0.1462	944	138.0	971	141.9	
	(iv) 0.1697	824	139.8	749	127.1	
	(v) 0.1931	685	132.3	749	144.6	
			767.7		766.9	+0.1

TABLE A2

Volume Flow Rates

Time (minutes)	CO_2 source at Front (ppm)	CO_2 source in middle (ppm)	CO_2 source in rear (ppm)	CO_2 source in rear* (ppm)
0	400	400	550	400
4	1300	750	850	500
8	2200	1750	1750	1150
12	3200	2900	2350	2300
16	3700	3600	2900	3250
20	3600	3800	3200	3650
24	4250	4200	3550	3800
28	4100	4400	3700	4200
32	4100	4550	3800	4150
36	4100	4600	4000	4200
40	4100	4700	4200	4250

NOTE: * - concentration measured in the front of the bus, as opposed to the conditioned air ducts.

CO_2 flow rate set at 35 scfh.

TABLE A3

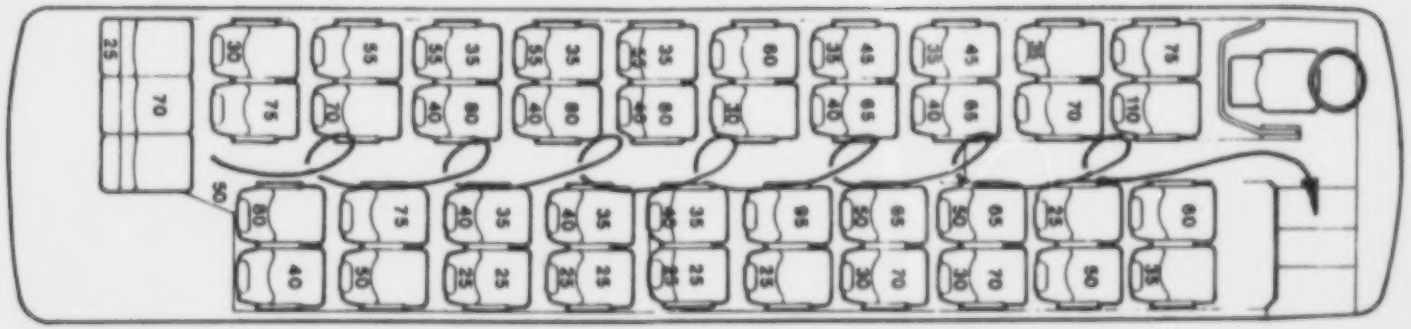
Carbon Dioxide Concentrations

FLOW SKETCHES

(Stationary Coach)

Average Air Velocities (fpm)

	Left	Right
Head Level	25.6	38.7
Seat Level	60.6	51.3
Overall	43.1	44.8



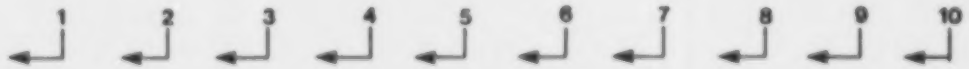


FIGURE A1

Overall Flow Sketch (Stationary Coach)

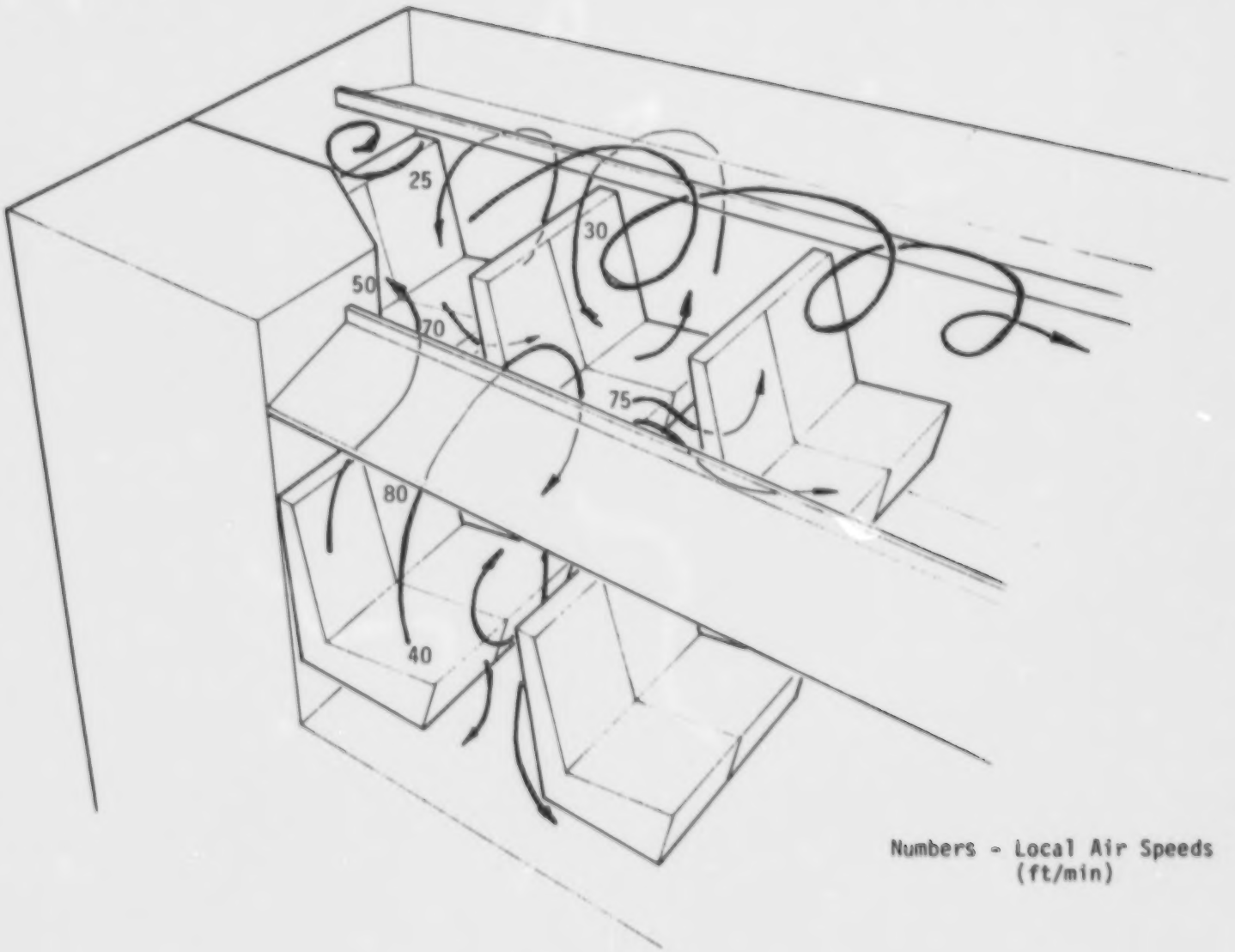
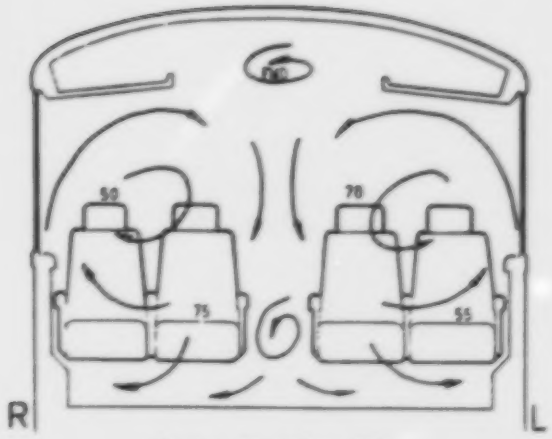
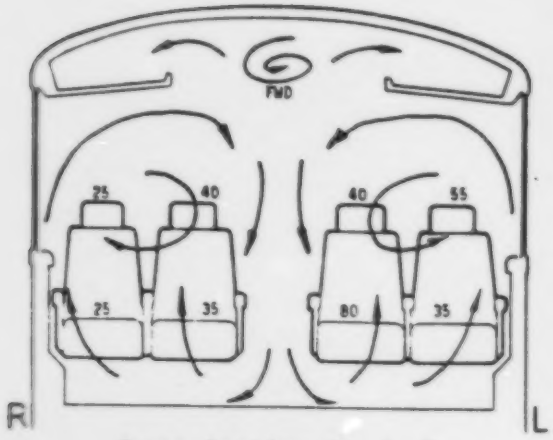


FIGURE A2

Rear Section Flow Sketch (Stationary Coach)



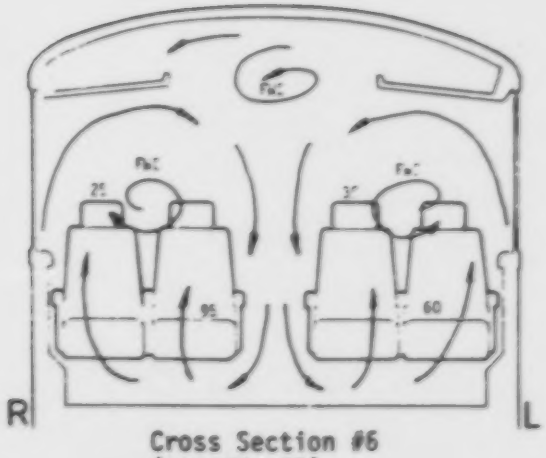
Cross Section #2
(see Fig A1)



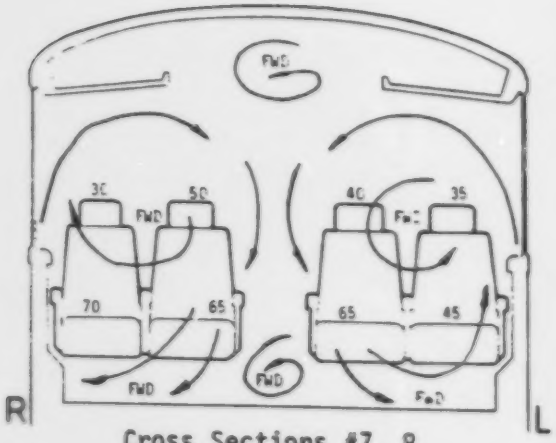
Cross Sections #3, 4, 5
(see Fig A1)

FIGURE A3

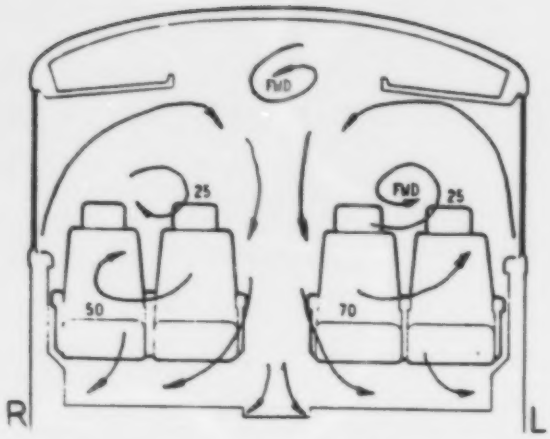
Cross Section Flow Sketches (Stationary Coach)



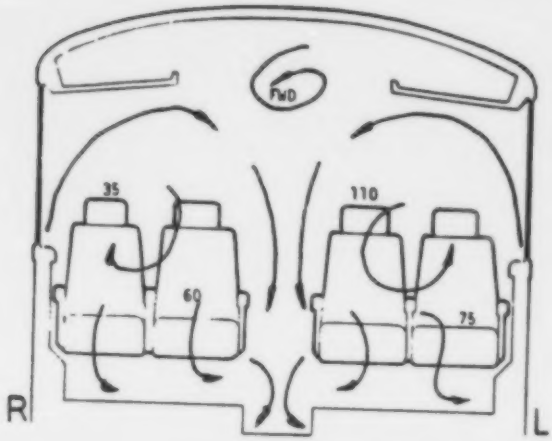
Cross Section #6
(see Fig A1)



Cross Sections #7, 8
(see Fig A1)



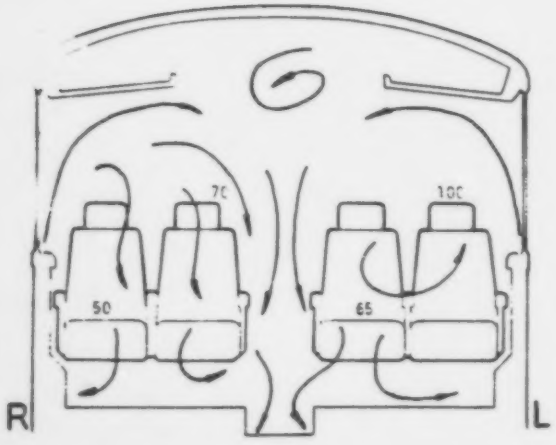
Cross Section #9
(see Fig A1)



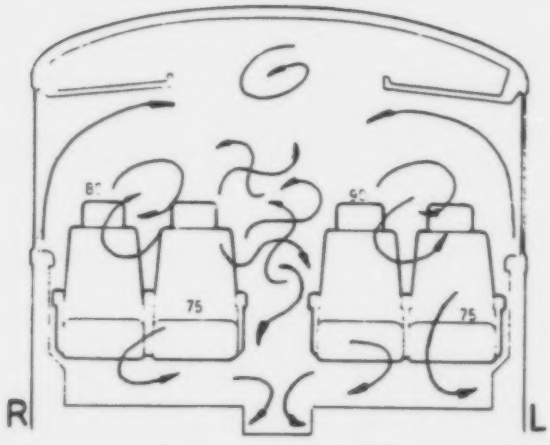
Cross Section #10
(see Fig A1)

FIGURE A4

Cross Section Flow Sketches (Stationary Coach)



Cross Section #9
(see Fig A1)
(Driver's System On)



Cross Section #10
(see Fig A1)
(Driver's System On)

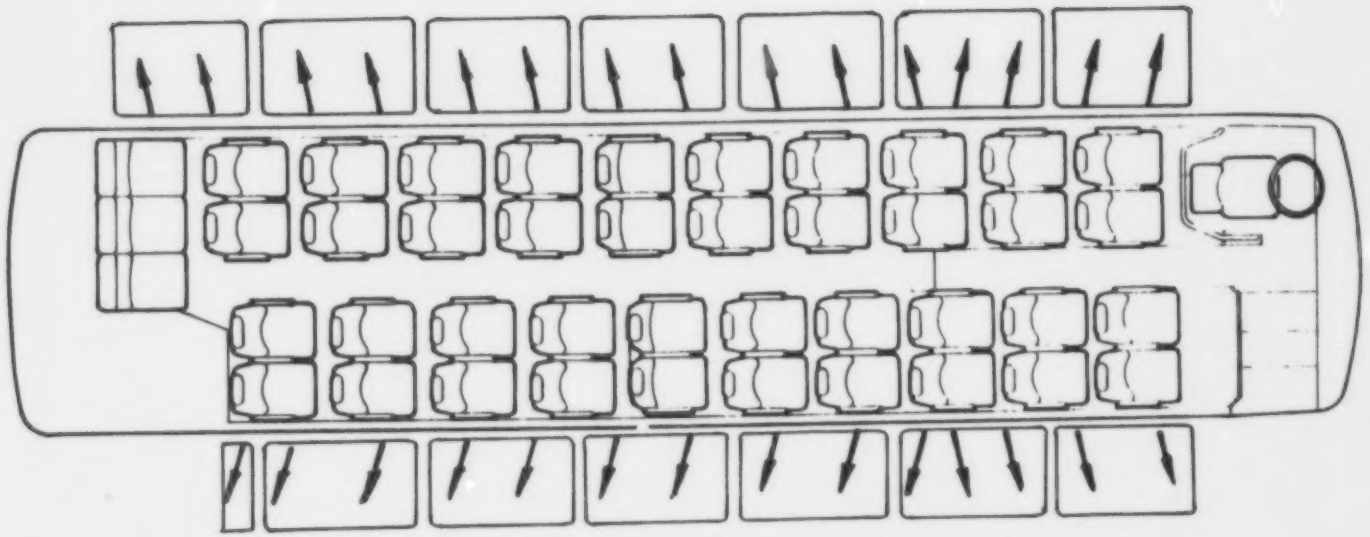


FIGURE A5

Air Flow Direction Exiting Diffuser

FLOW SKETCHES

(Highway Speed Coach)

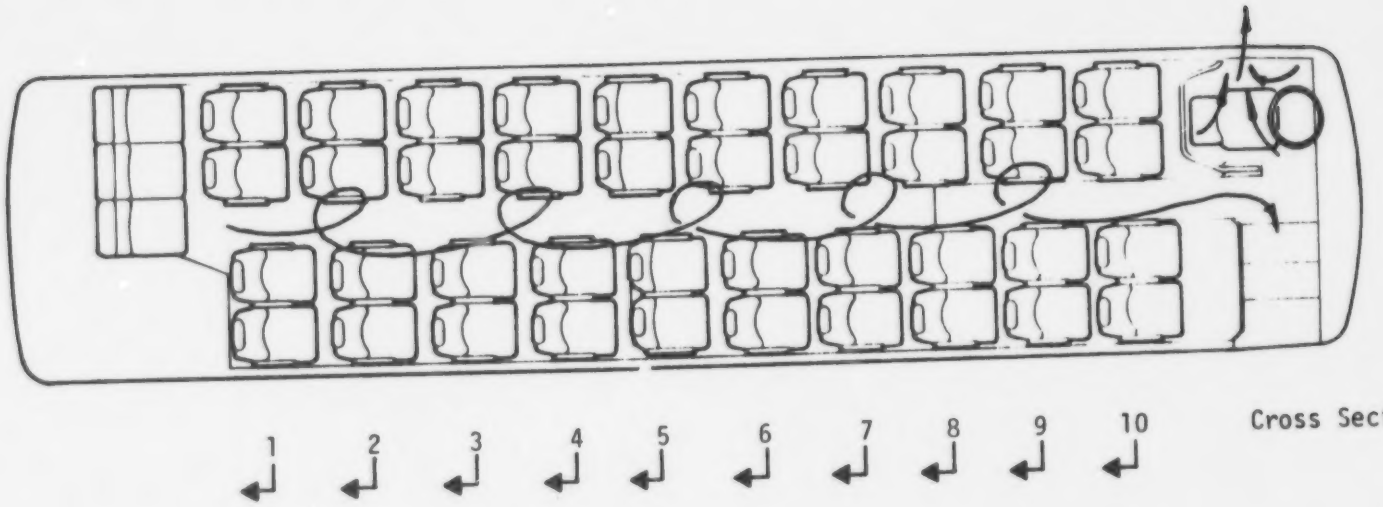


FIGURE A6

Overall Flow Sketch (Highway Speed Coach)

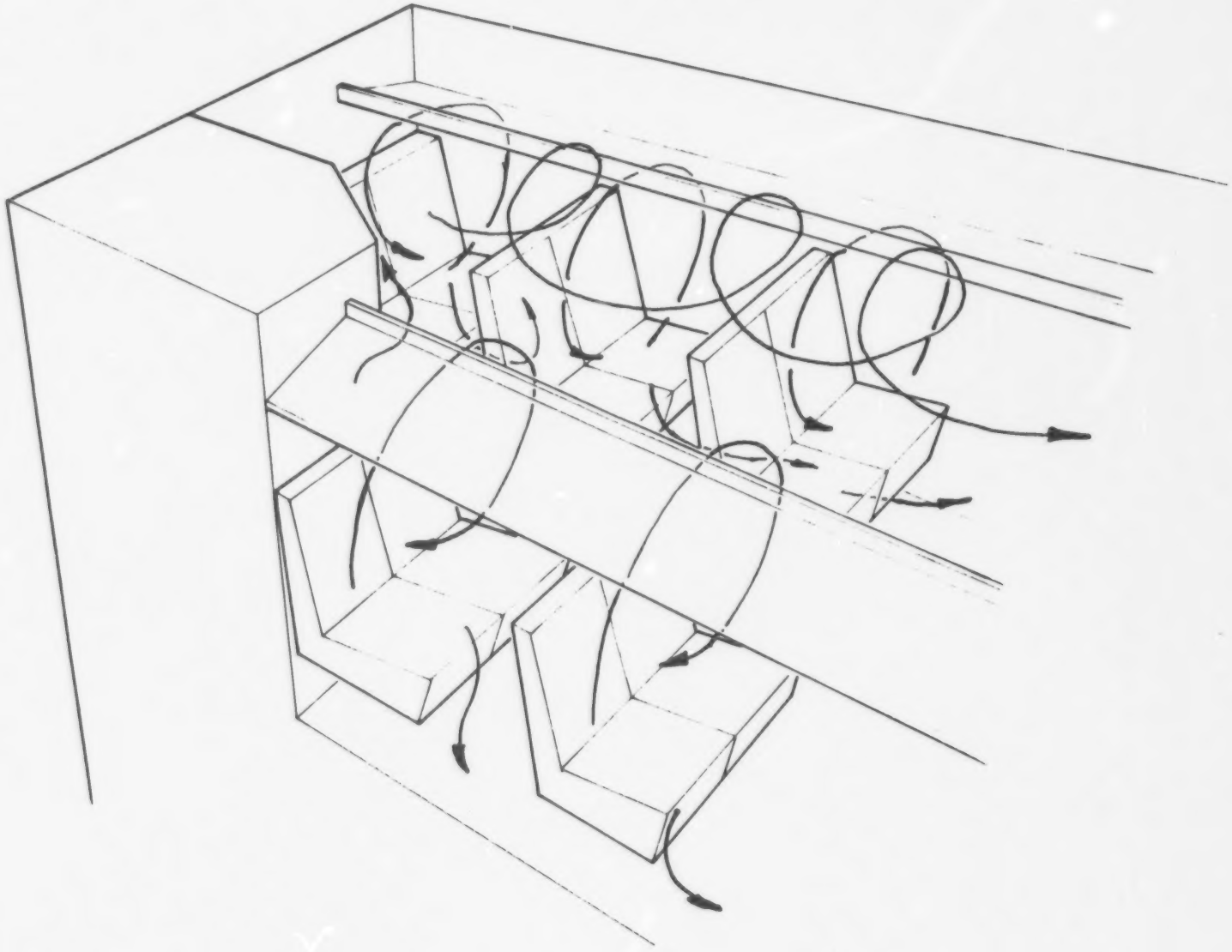
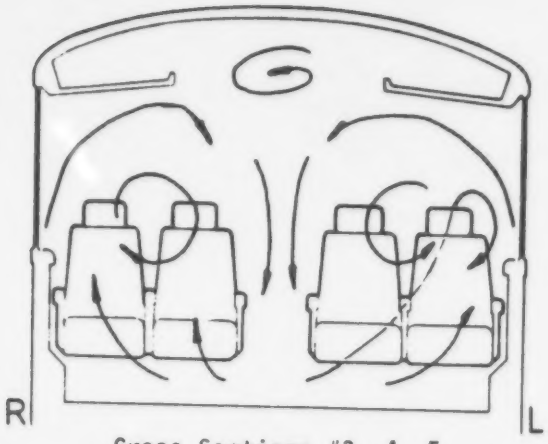
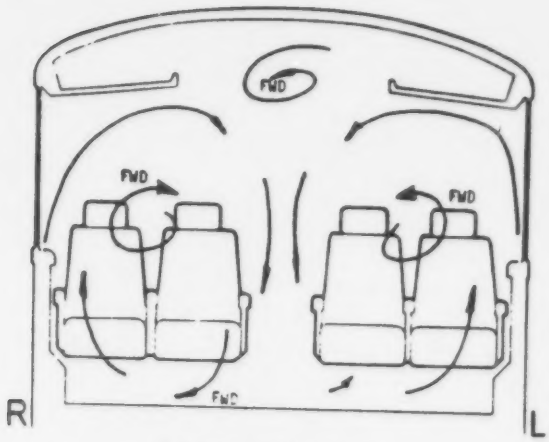


FIGURE A7

Rear Sect Flow Sketch (High ed Coach)



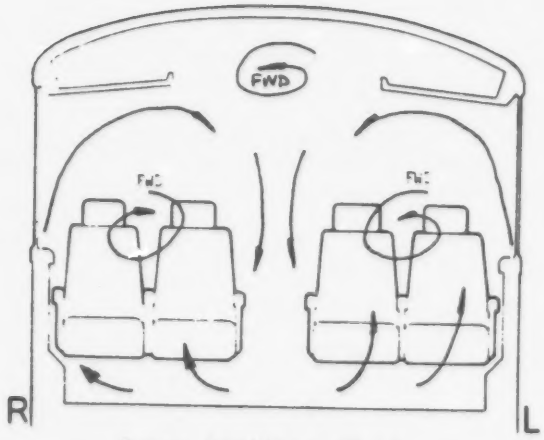
Cross Sections #3, 4, 5
(see Fig A6)



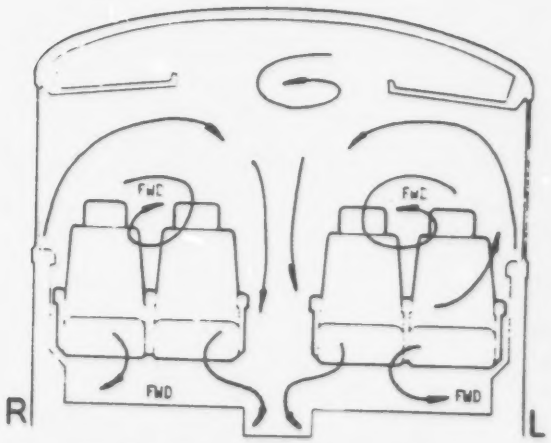
Cross Section #6
(see Fig A6)

FIGURE A8

Cross Section Flow Sketches (Highway Speed Coach)



Cross Sections #7, 8
(see Fig A6)



Cross Sections #9, 10
(see Fig A6)

FLOW SKETCHES

(Occupied Coach)

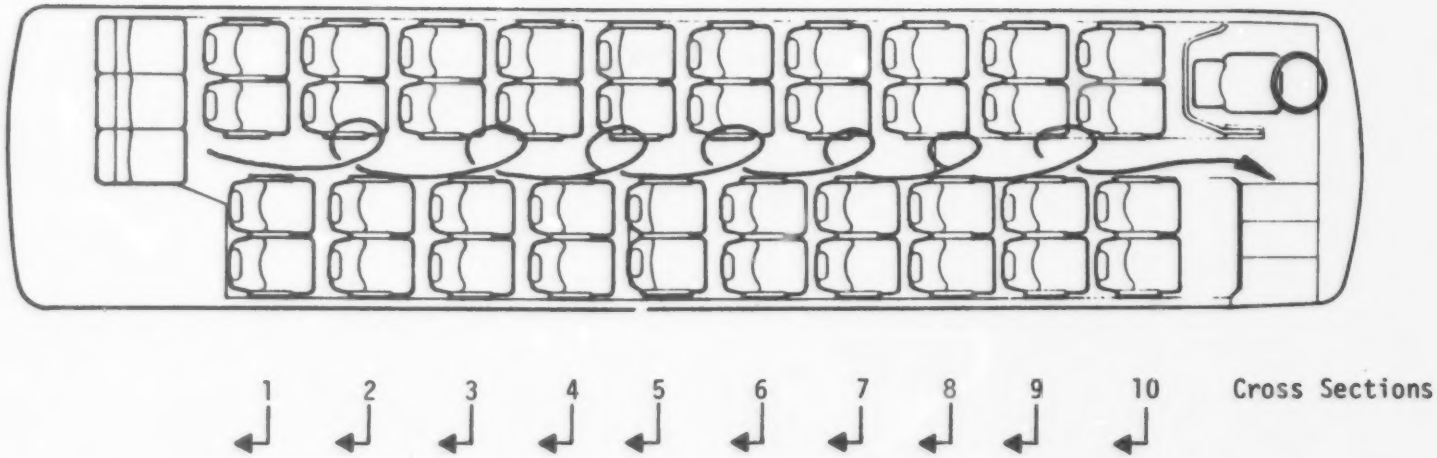


FIGURE A9

Overall Flow Sketch (Occupied Coach)

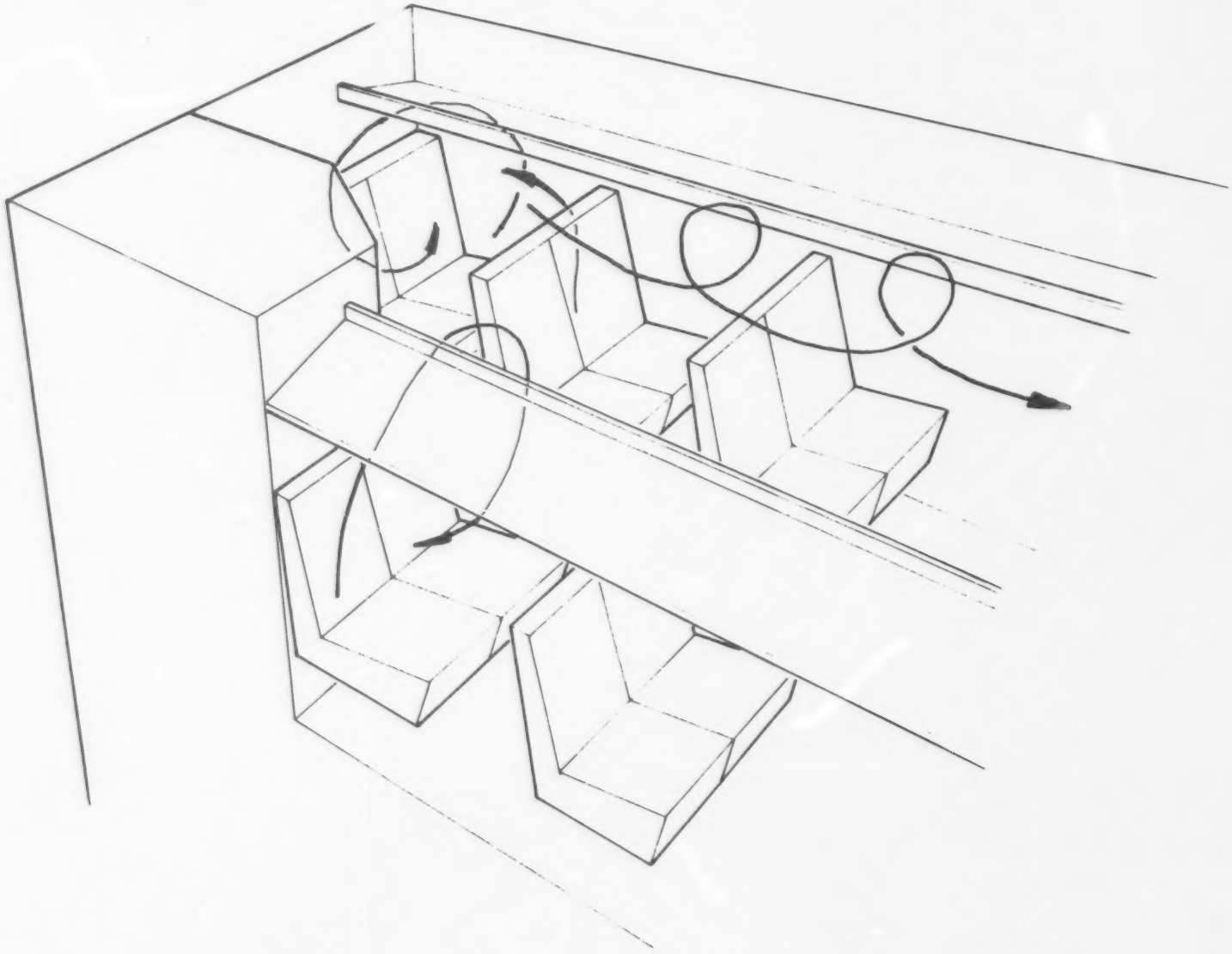
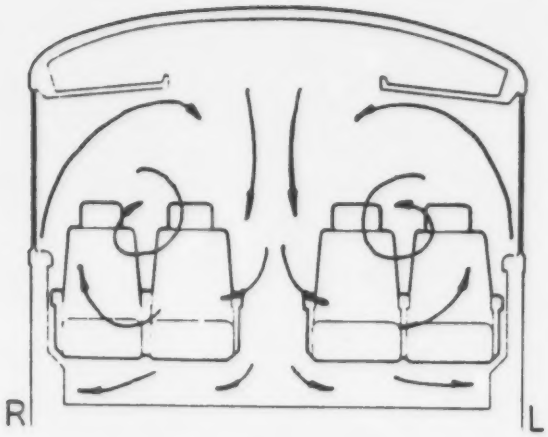
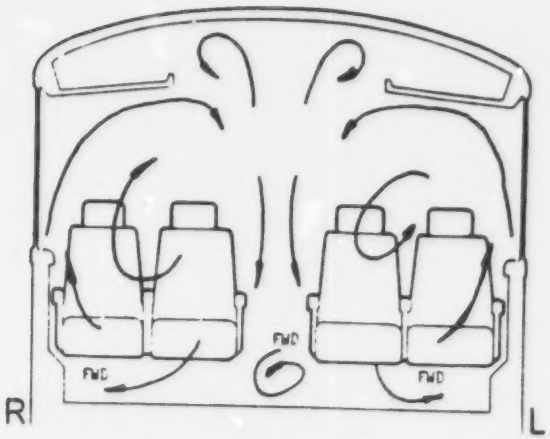


FIGURE A10

Rear Sec'. Flow Sketch (Occupied Coach)



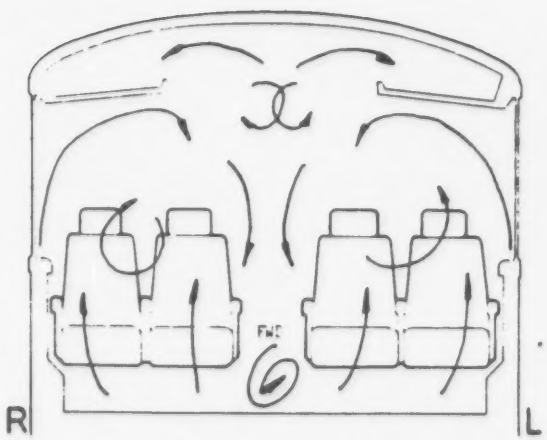
Cross Section #1
(see Fig A9)



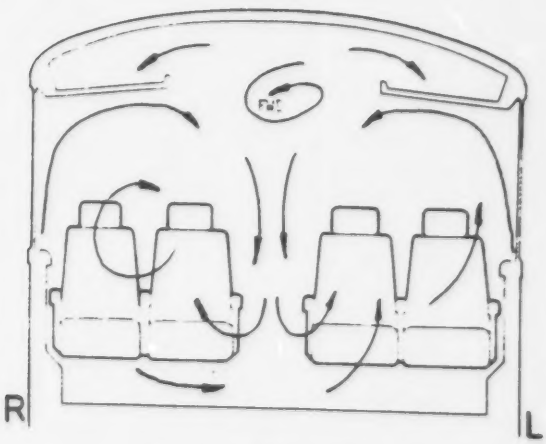
Cross Sections #2, 3
(see Fig A9)

FIGURE A11

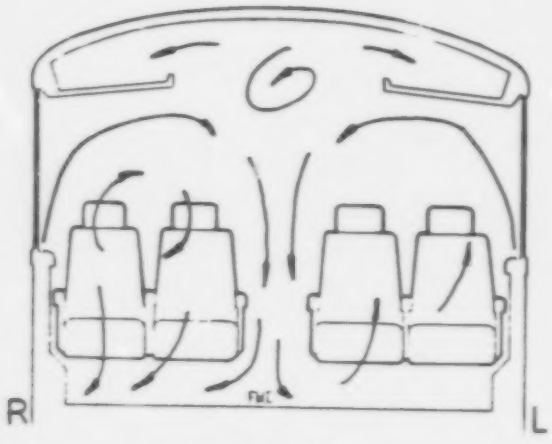
Cross Section Flow Sketches (Occupied Coach)



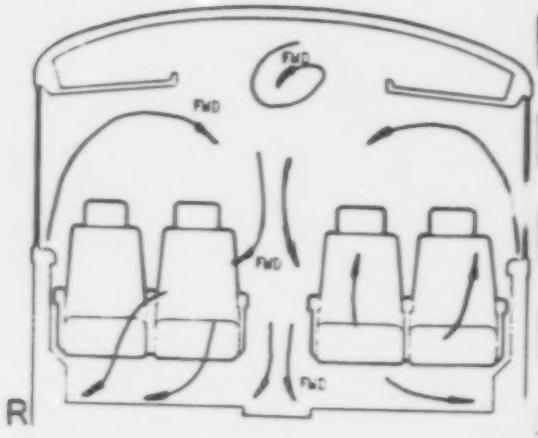
Cross Sections #4, 5
(see Fig A9)



Cross Section #6
(see Fig A9)



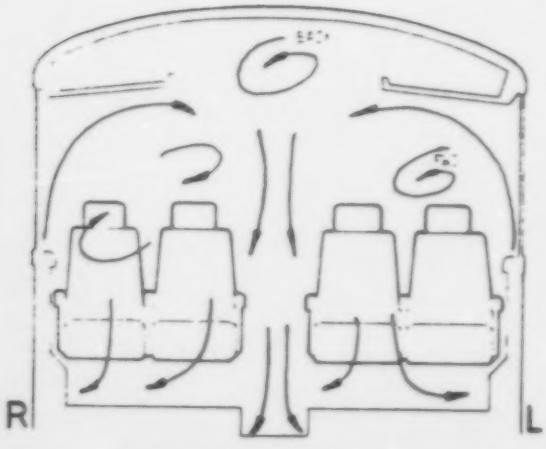
Cross Section #7
(see Fig A9)



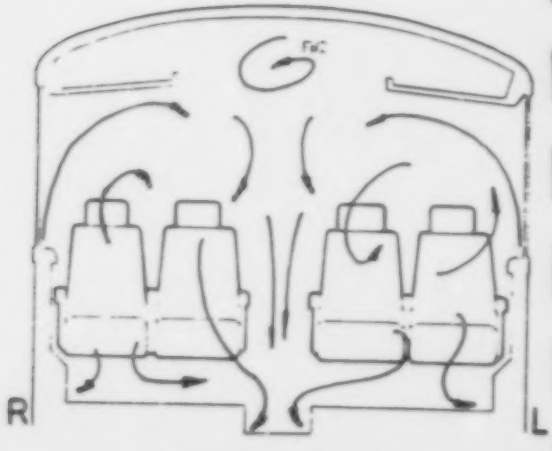
Cross Section #8
(see Fig A9)

FIGURE A12

Cross Section Flow Sketches (Occupied Coach)



Cross Section #9
(see Fig A9)



Cross Section #10
(see Fig A9)

AIR SPEED PROFILES

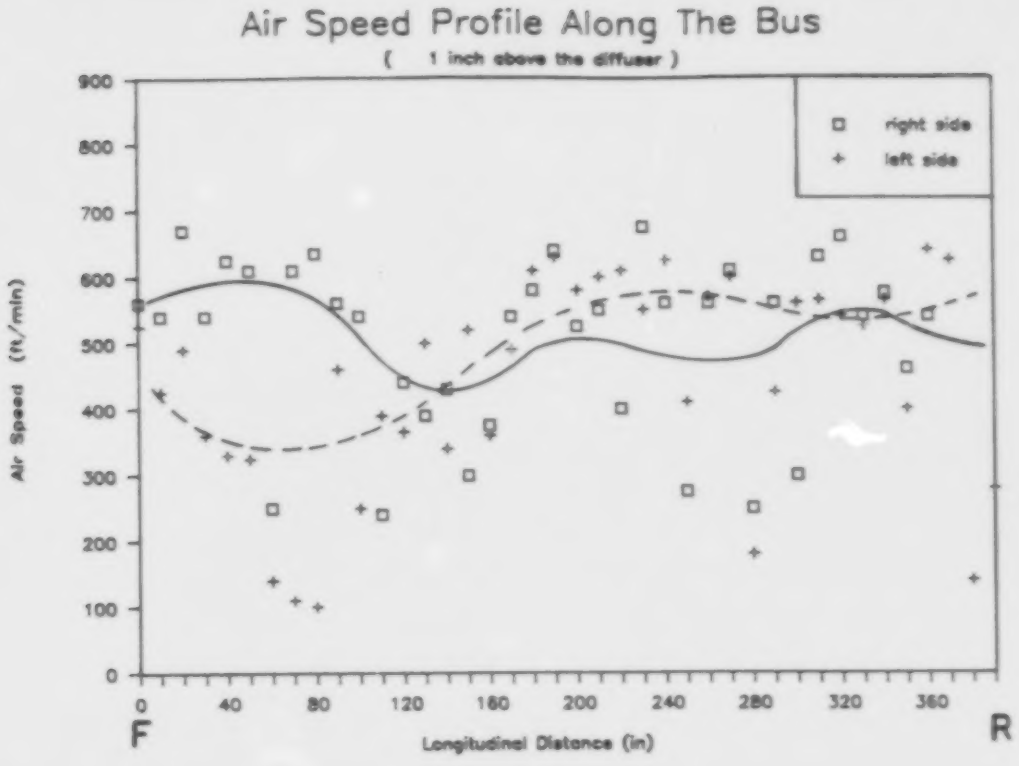


FIGURE A13

Air Speed Profiles (1 Inch Above Diffuser)

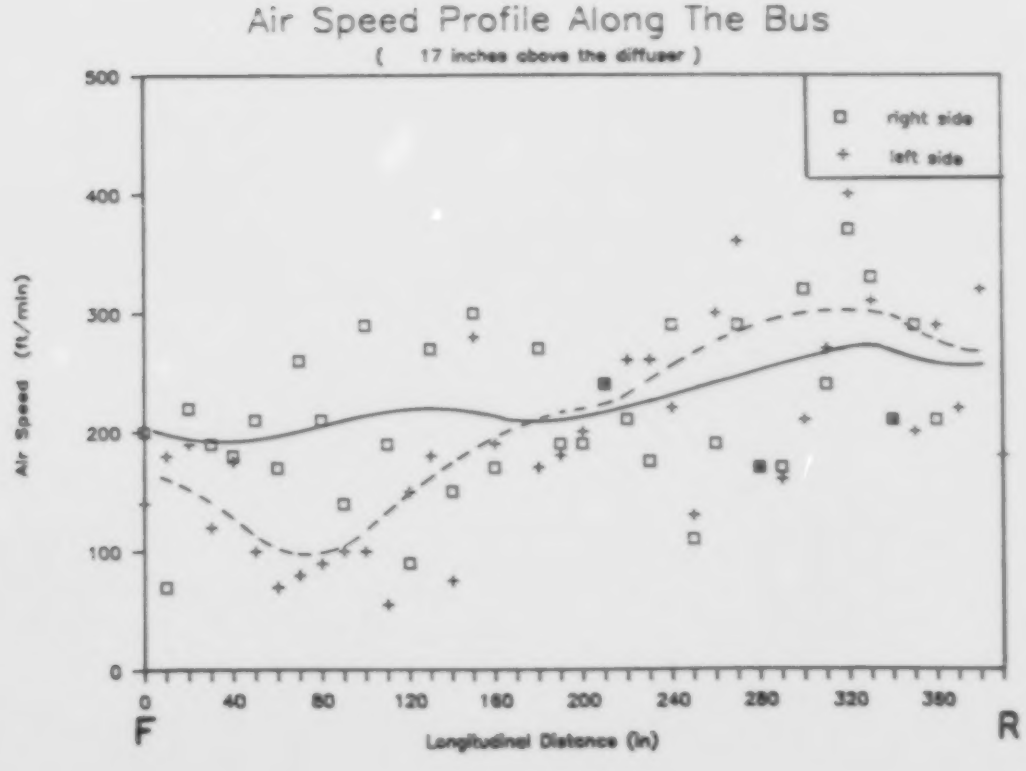


FIGURE A14

Air Speed Profiles (17 Inches Above Diffuser)

TEMPERATURE PROFILES

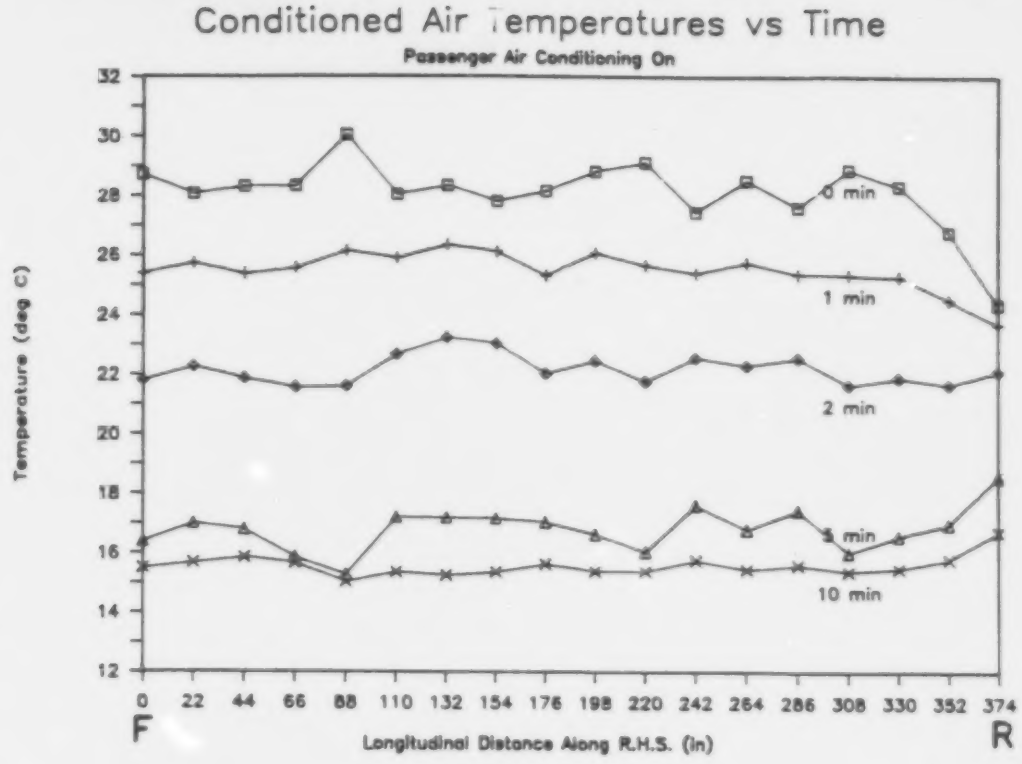


FIGURE A15

Coach RHS Temperature Profiles (Cooling Mode)

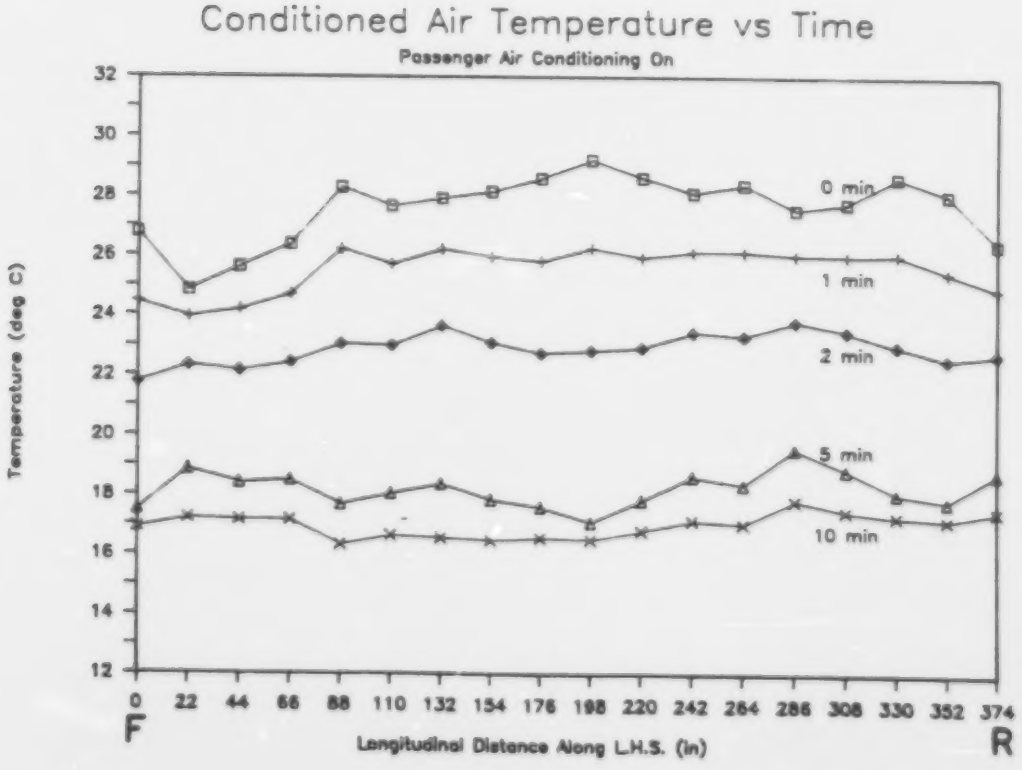


FIGURE A16

Coach LHS Temperature Profiles (Cooling Mode)

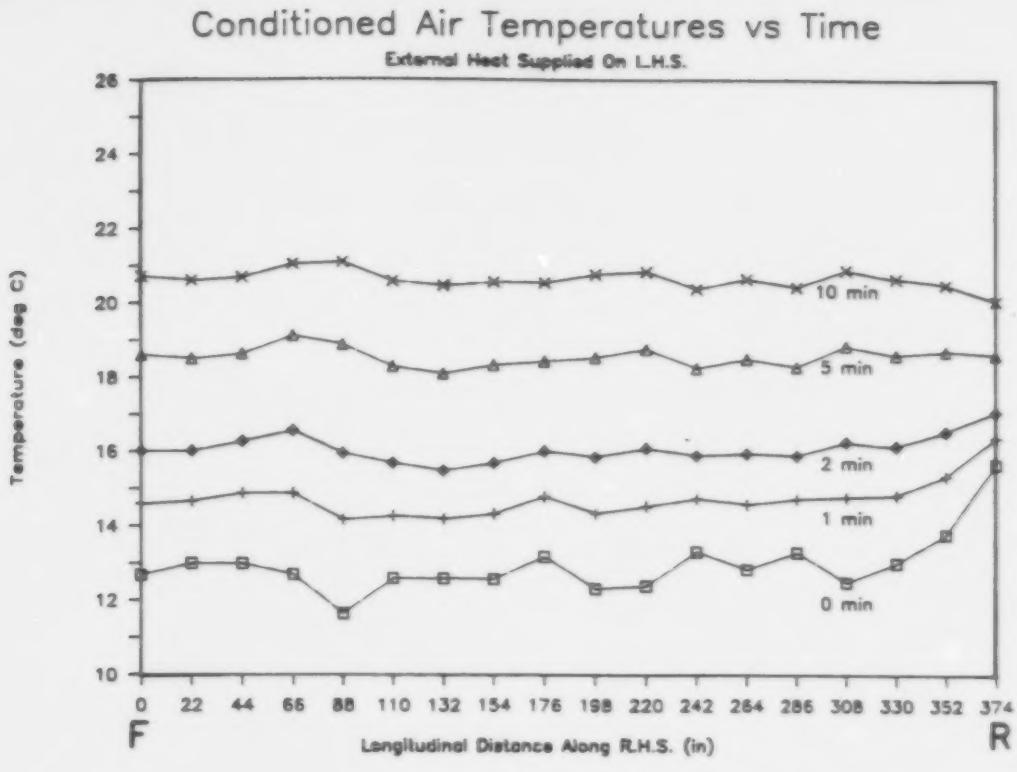


FIGURE A17

Coach RHS Temperature Profiles (External Heat Source)

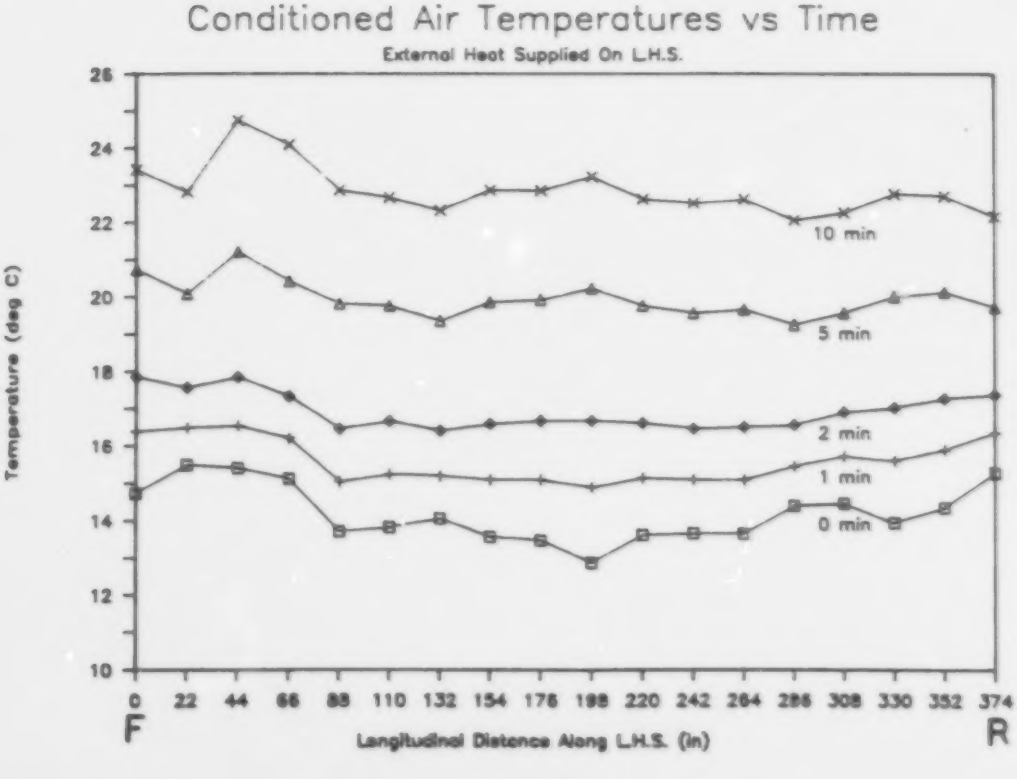


FIGURE A18

Coach LHS Temperature Profiles (External Heat Source)

CARBON DIOXIDE CONCENTRATIONS

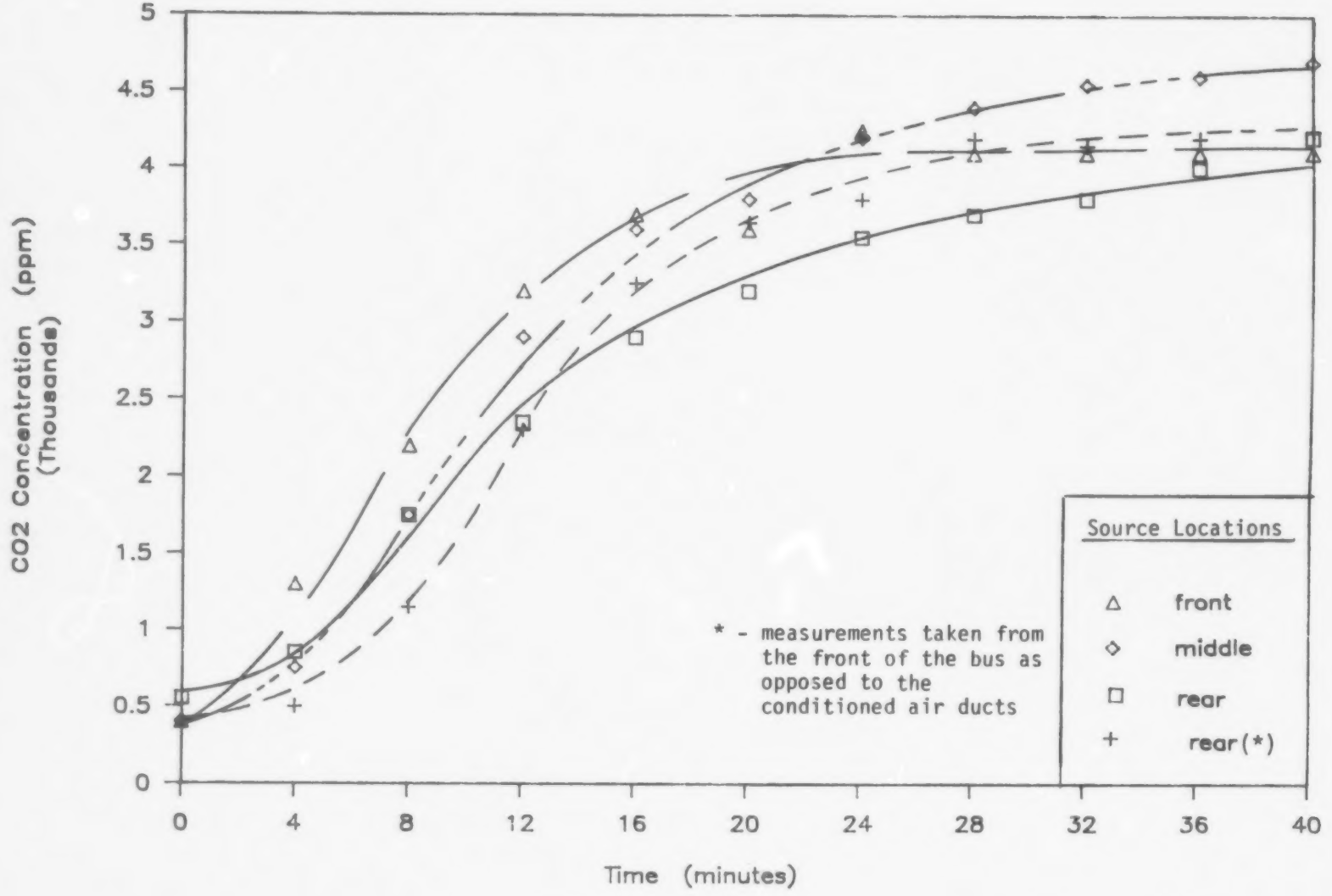


FIGURE A19

Carbon Dioxide Concentrations Versus Time

ANNEX B

Test Results: Prevost Marathon XL

ANNEX B

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TABLE B1	-	Volume Flow Rate Summary
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TABLE B3	-	Carbon Dioxide Concentrations

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FIGURE B4	-	Cross Section Flow Sketches (Stationary Coach)
FIGURE B5	-	Cross Section Flow Sketch (Stationary Coach)
FIGURE B6	-	Overall Flow Sketch (Highway Speed Coach)
FIGURE B7	-	Rear Section Flow Sketch (Highway Speed Coach)
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FIGURE B16	-	Coach LHS Temperature Profiles (External Heat Source)
FIGURE B17	-	Carbon Dioxide Concentrations Versus Time

DATA TABLES

Volume flow measurement locations	Component volume flows (ft^3/min)	Percentage of the total volume flow
A. Driver's system Recycled supply (high)	281.1	
B. Passenger Compartment		
1. Conditioned air ducts	(R) 1506 (L) 1041 2547	59.1 40.9
2. Fresh air intakes		
(i) Full closed	201.9	
(ii) Middle	219.3	8.6
(iii) Full open	230.9	
3. Washroom exhaust	68.8	2.7
4. Leakage		5.9
5. Recycled air (ii)	2221	87.2

TABLE B1

Volume Flow Rate Summary

Volume flow rate measurement locations	Cross Sectional Area (ft^2)	Stationary		Highway Speed (90 km/h)		% Difference between volume flow rates (%)
		Integrated air speed (ft/min)	Volume flow rate (ft^3/min)	Integrated air speed (ft/min)	Volume flow rate (ft^3/min)	
A. Driver's system						
1. Into evaporator	0.09850	611	60.2	504	49.6	-17.6
2. Out of defroster	0.01285	2463	31.6			
	0.01285	2299	29.5	1902	24.4	-17.4
	0.01285	2548	32.7			
	0.01285	1997	25.7	1643	21.1	-17.7
	0.01285	2181	28.0			
	0.01285	2759	35.4			
	0.01285	1511	19.4	1200	15.4	-20.6
	0.01285	2187	28.1			
	0.02182	2325	50.7			
			281.1			
B. Passenger Compartment						
1. Conditioned air ducts	(R) 0.2895	5202	1506	-	-	
	(L) 0.3056	3405	1041	-	-	
2. Fresh air intake (i)	0.09850	2049	201.9	-	-	
(ii)	0.09850	2227	219.3	-	-	
(iii)	0.09850	2345	230.9	-	-	
3. Washroom exhaust	.02182	3199	69.8	-	-	
4. Recycled air	1.125	1974	2221	2114	2378	+7.1%

TABLE B2

Volume Flow Rates

Time (minutes)	CO_2 source at Front (ppm)	CO_2 source in middle (ppm)	CO_2 source in rear (ppm)
0	550	550	550
4	700	1100	650
6	1050	1600	1350
8	1350	1900	1600
10	1700	2700	2200
12	1700	2900	2700
14	-	3000	2800
16	1900	3100	3100
18	2300	3200	3000
20	2500	3200	-
22	2400	3300	3100
24	2400	-	3200
26	2500	3350	3150

NOTE: CO_2 concentrations measured in the conditioned air ducts.
CO_2 flow rate set at 35 scfh.

TABLE B3

Carbon Dioxide Concentrations

FLOW SKETCHES

(Stationary Coach)

Average Air Velocities (fpm)

	Left	Right
Head Level	49.7	32.7
Seat Level	56.7	46.4
Overall	53.2	39.3

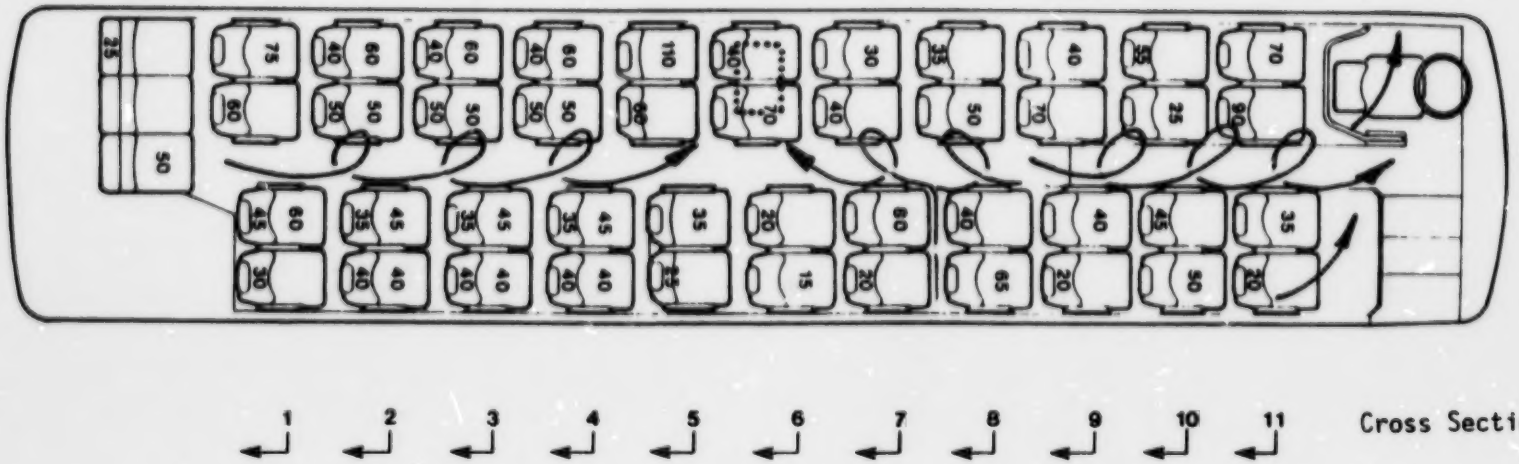
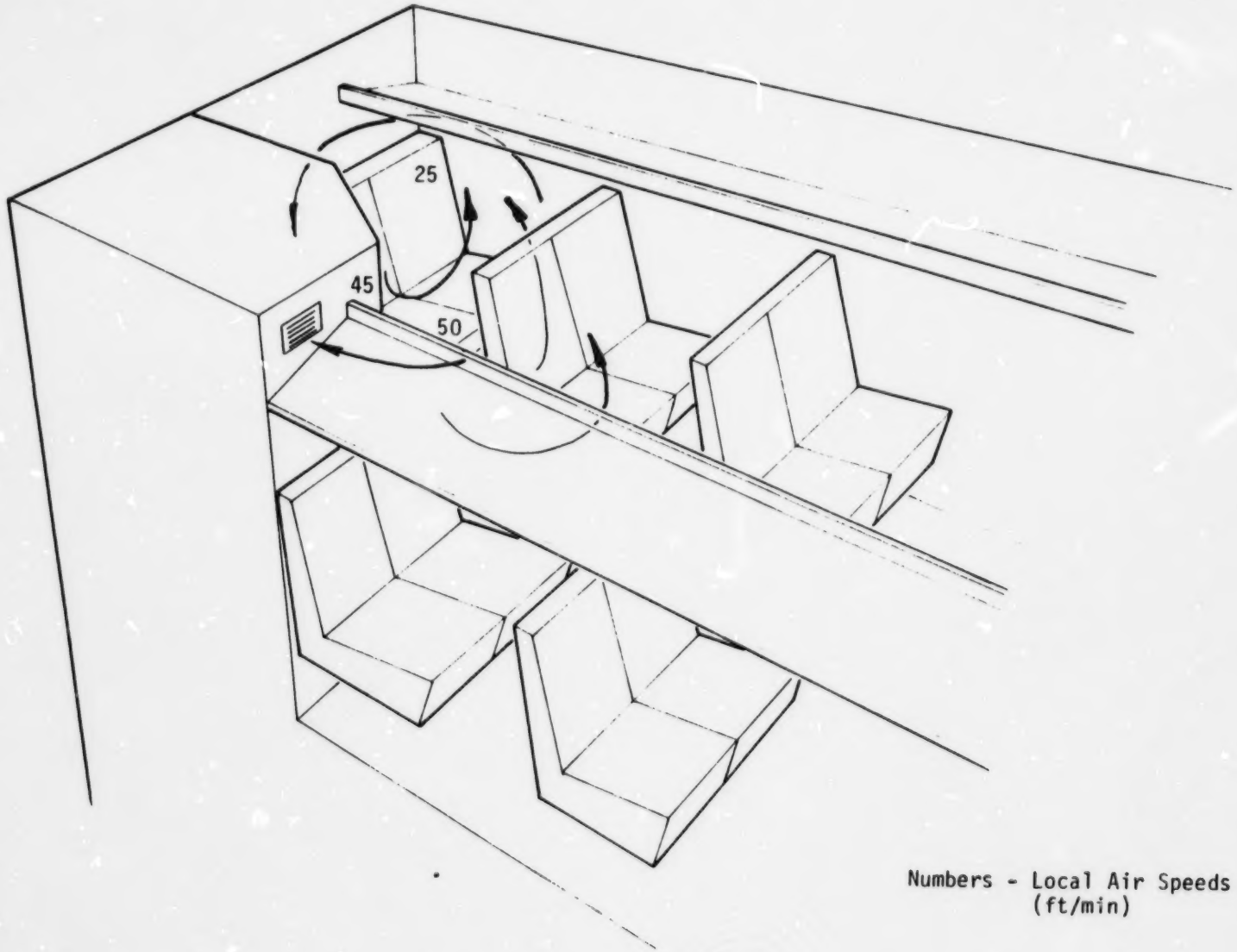


FIGURE B1

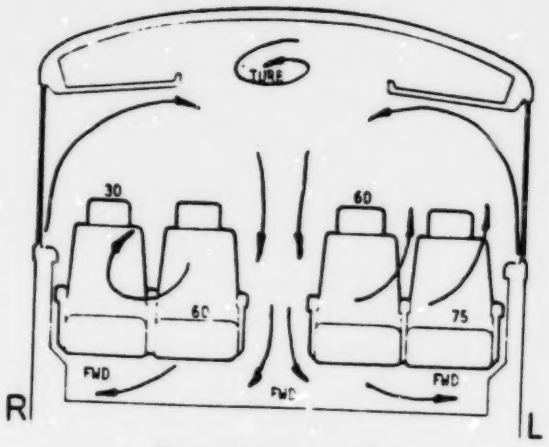
Overall Flow Sketch (Stationary Coach)



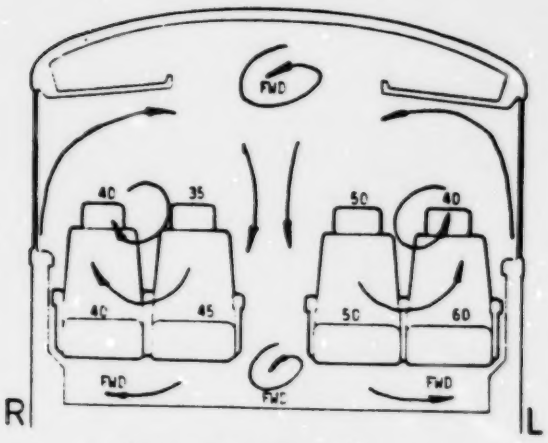
Numbers - Local Air Speeds
(ft/min)

FIGURE B2

Rear Section Flow Sketch (Stationary Coach)



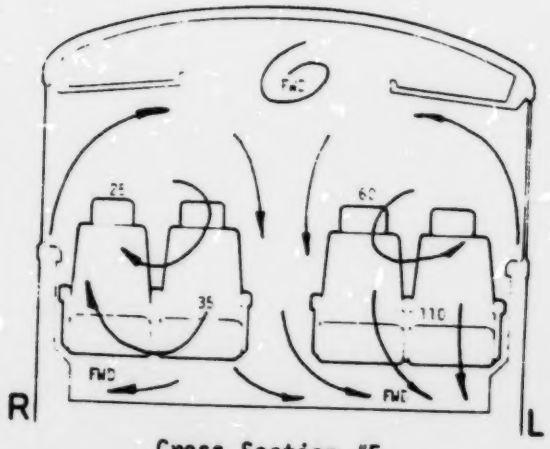
Cross Section #1
(see Fig B1)



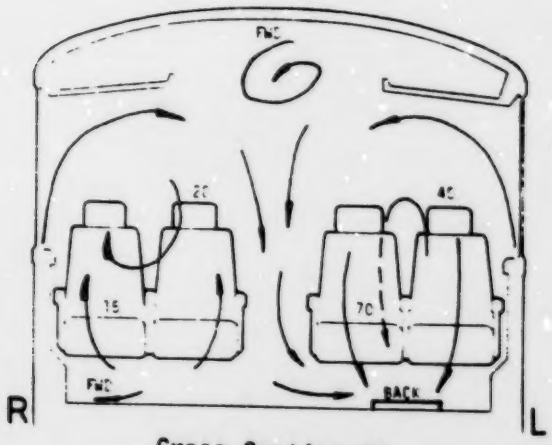
Cross Sections #2, 3, 4
(see Fig B1)

FIGURE B3

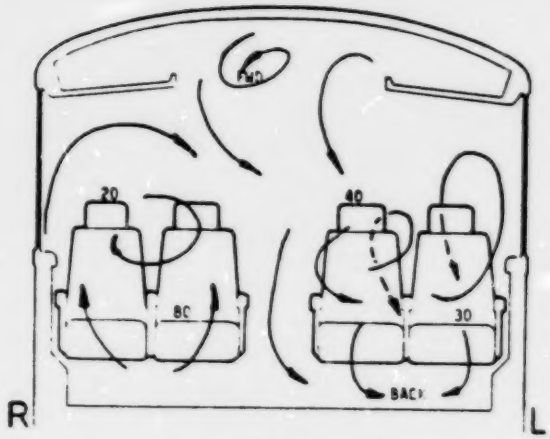
Cross Section Flow Sketches (Stationary Coach)



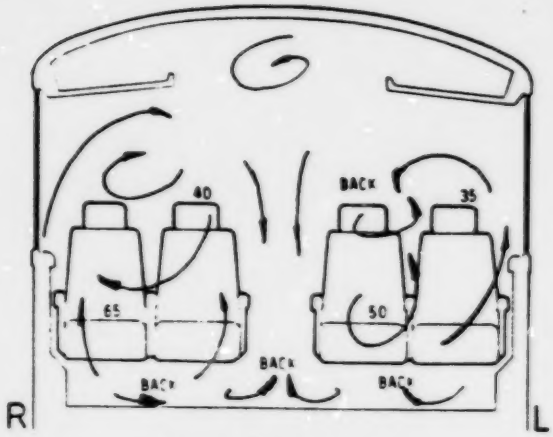
Cross Section #5
(see Fig B1)



Cross Section #6
(see Fig B1)



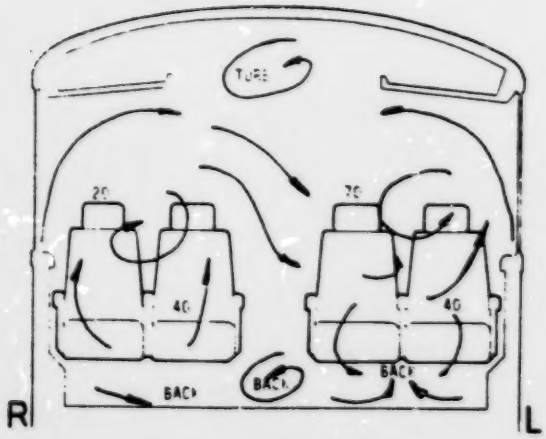
Cross Section #7
(see Fig B1)



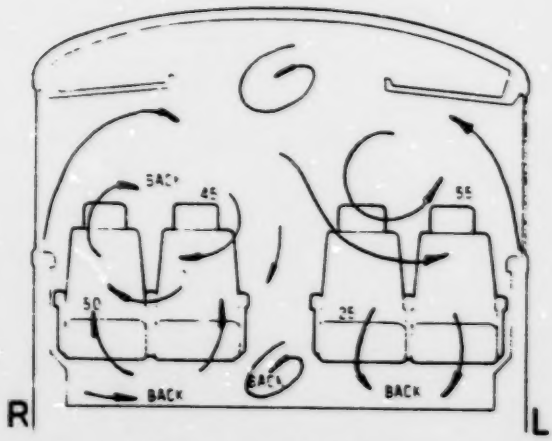
Cross Section #8
(see Fig B1)

FIGURE B4

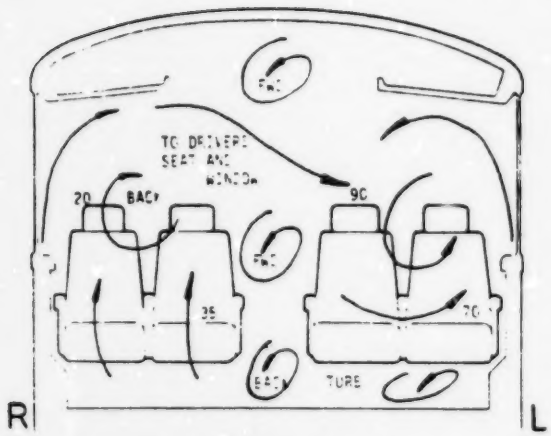
Cross Section Flow Sketches (Stationary Coach)



Cross Section #9
(see Fig B1)



Cross Section #10
(see Fig B1)



Cross Section # 11
(see Figure B1)

FIGURE B5

Cross Section Flow Sketch (Stationary Coach)

FLOW SKETCHES

(Highway Speed Coach)

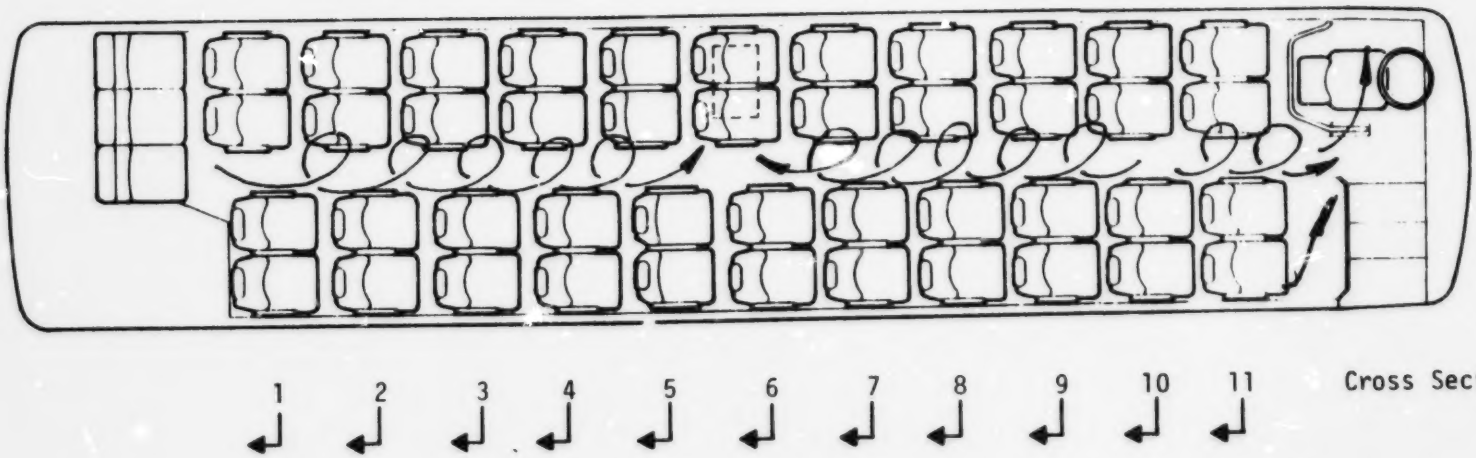


FIGURE B6

Overall Flow Sketch (Highway Speed Coach)

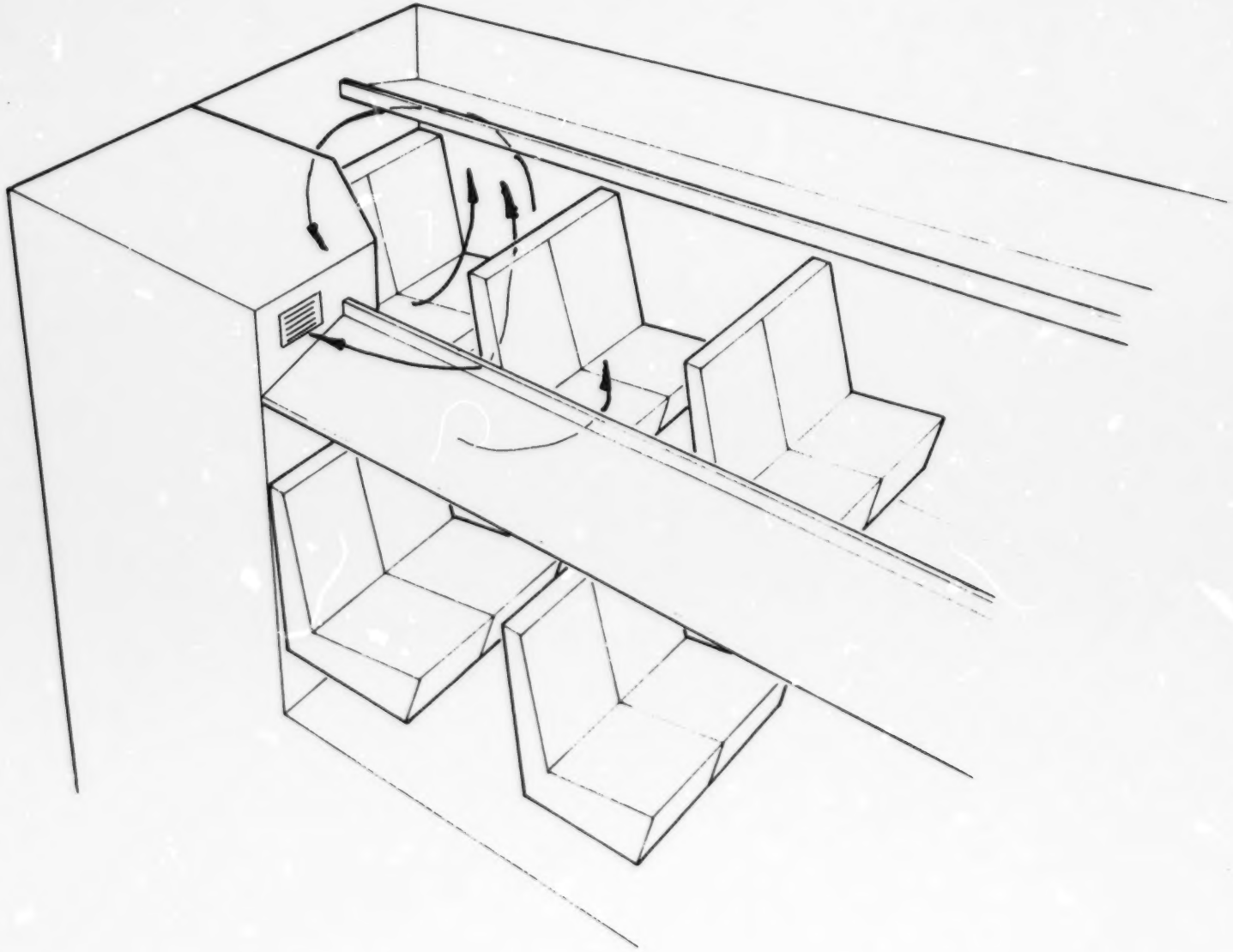
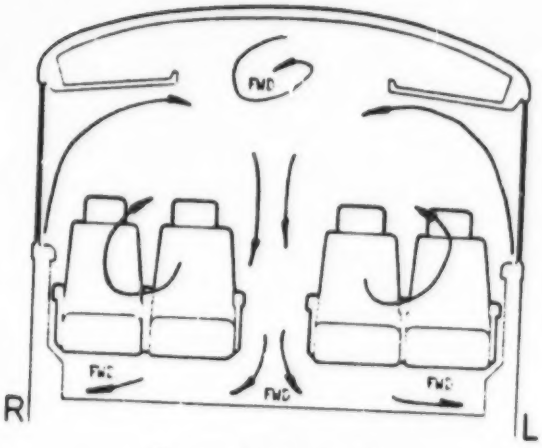
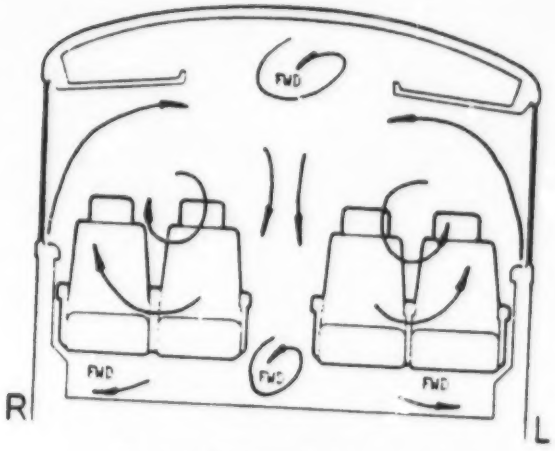


FIGURE B7

Rear Section Flow Sketch (Highway Speed Coach)



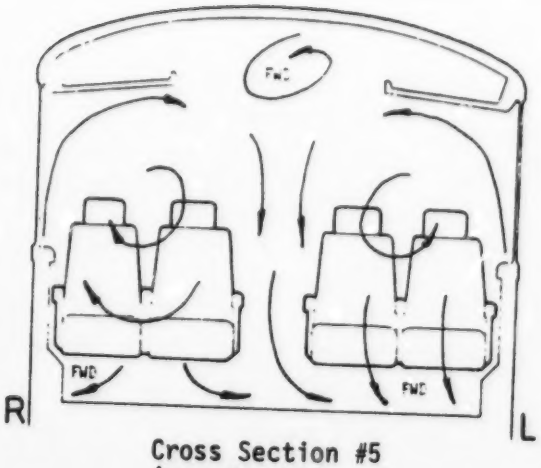
Cross Section #1
(see Fig B6)



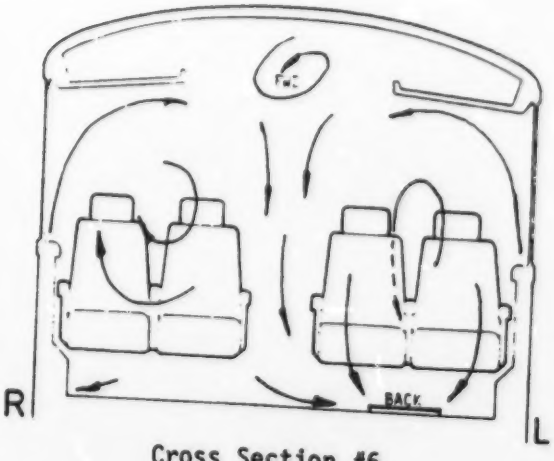
Cross Sections #2, 3, 4
(see Fig B6)

FIGURE B8

Cross Section Flow Sketches (Highway Speed Coach)



Cross Section #5
(see Fig B6)



Cross Section #6
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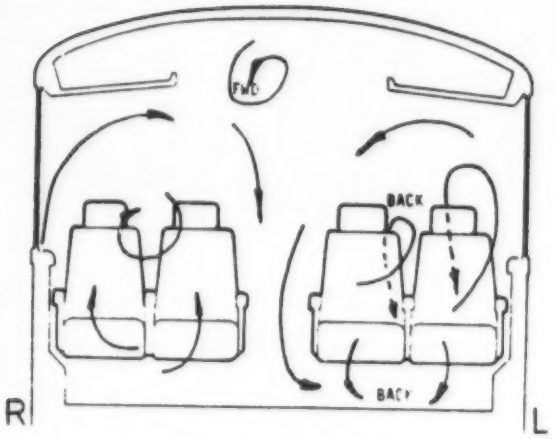

Cross Section #7
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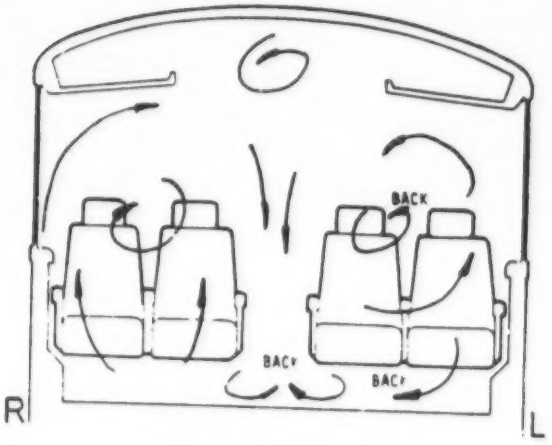
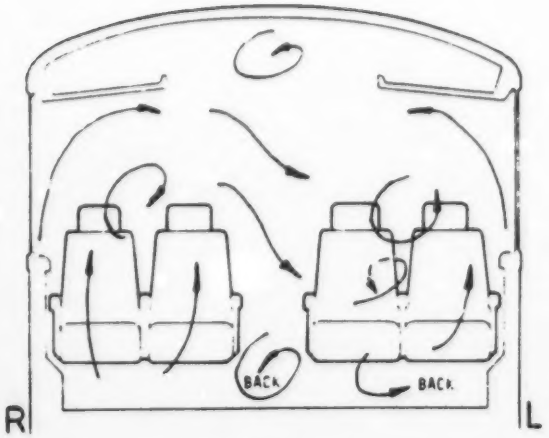


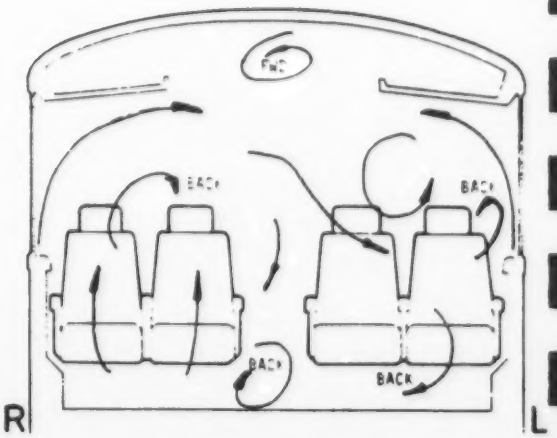
Cross Section #8
(see Fig B6)

FIGURE B9

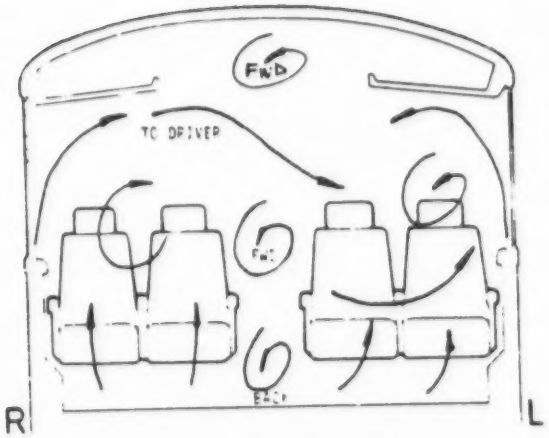
Cross Section Flow Sketches (Highway Speed Coach)



Cross Section #9
(see Fig B6)



Cross Section #10
(see Fig B6)



Cross Section #11
(see Fig B6)

FIGURE B10

Cross Section Flow Sketch (Highway Speed Coach)

AIR SPEED PROFILES

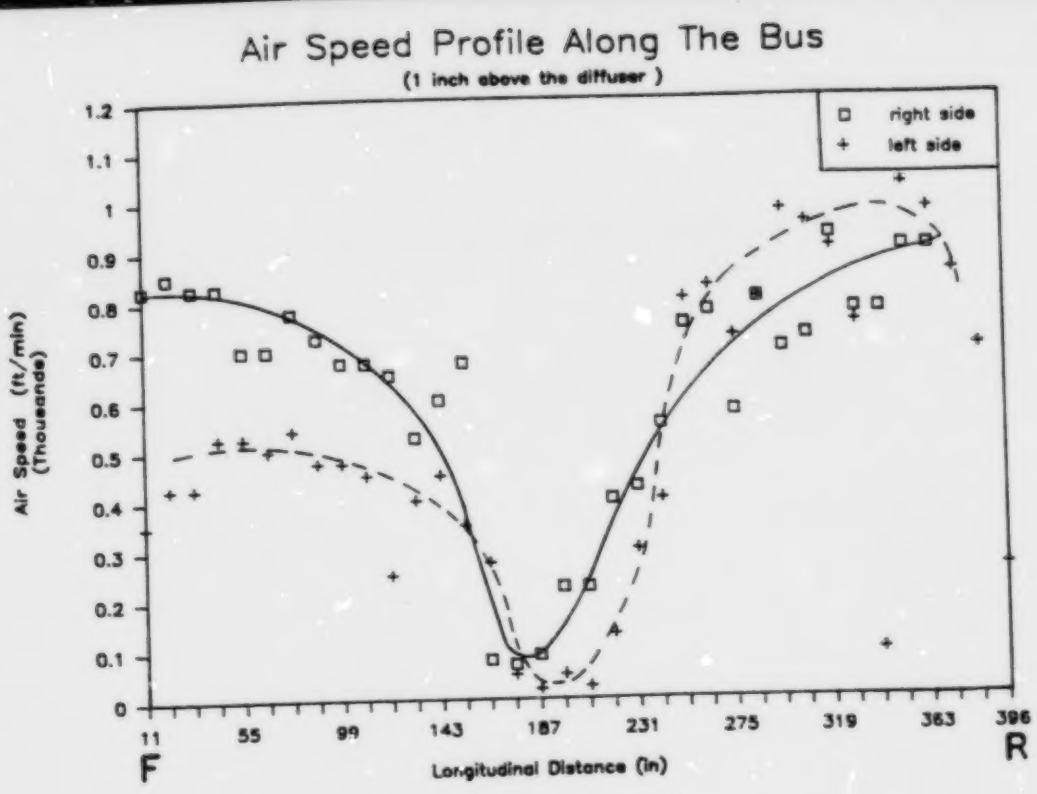


FIGURE B11

Air Speed Profiles (1 Inch Above Diffuser)

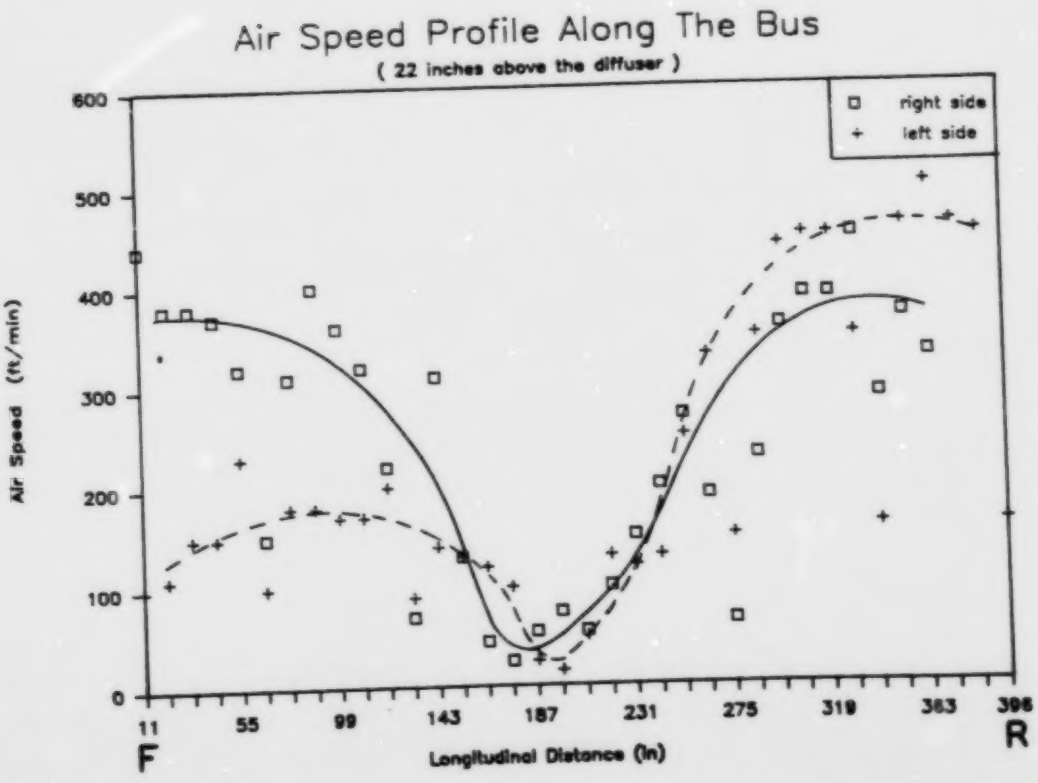


FIGURE B12

Air Speed Profiles (22 Inches Above Diffuser)

TEMPERATURE PROFILES

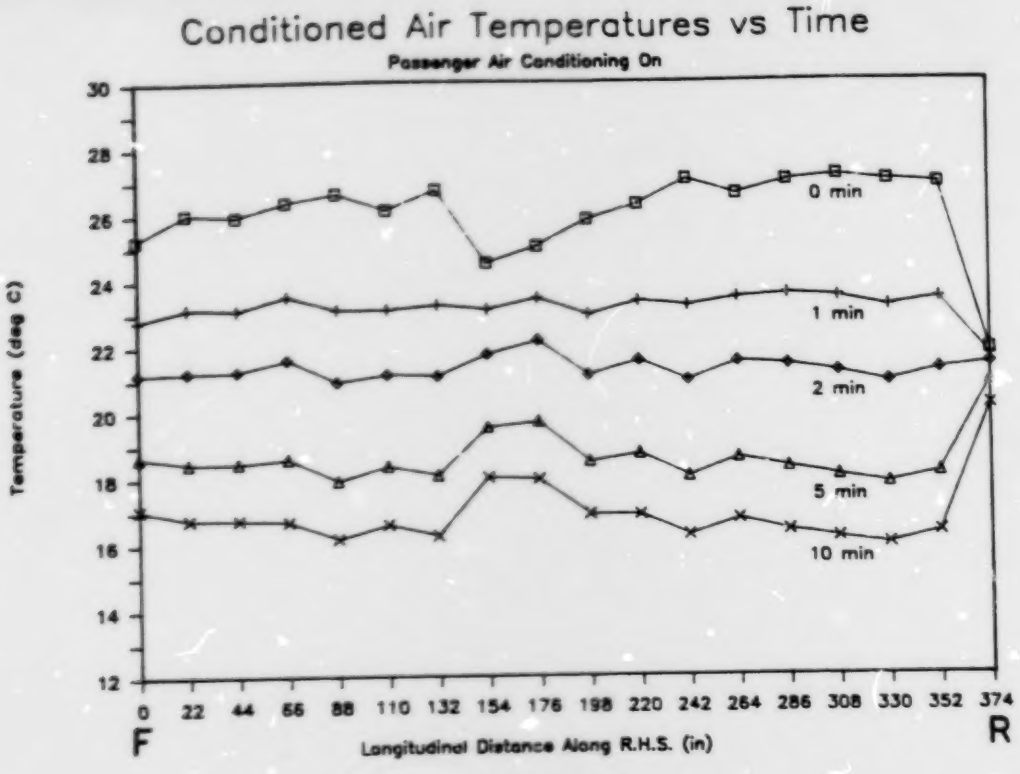


FIGURE B13

Coach RHS Temperature Profiles (Cooling Mode)

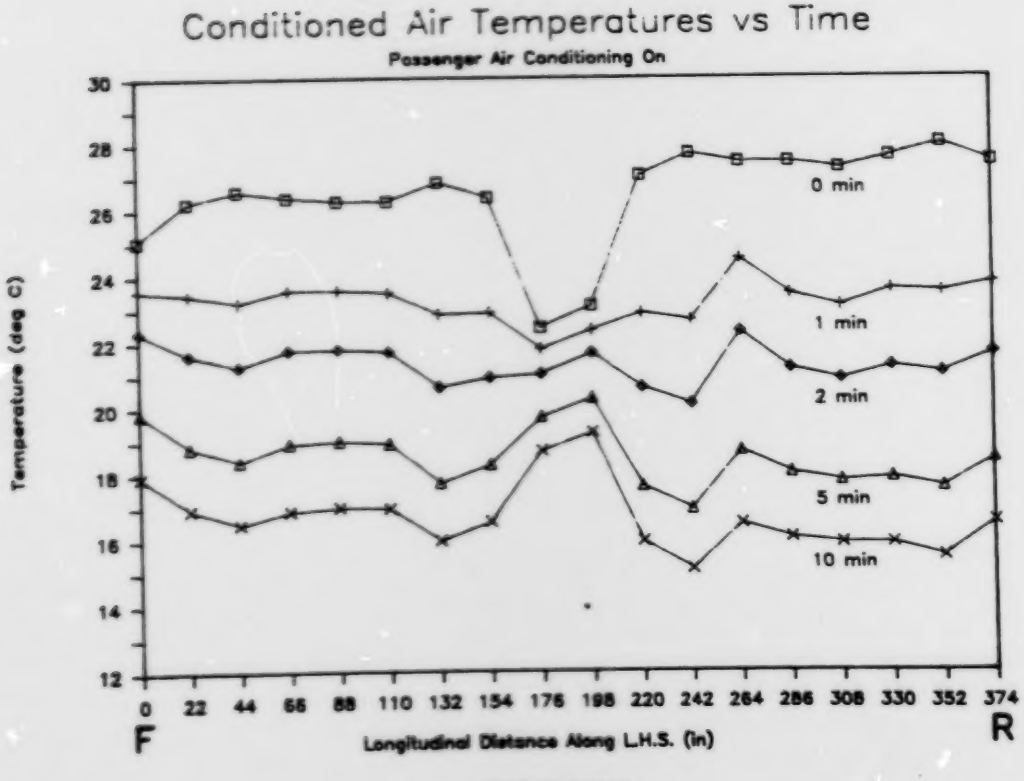


FIGURE B14

Coach LHS Temperature Profiles (Cooling Mode)

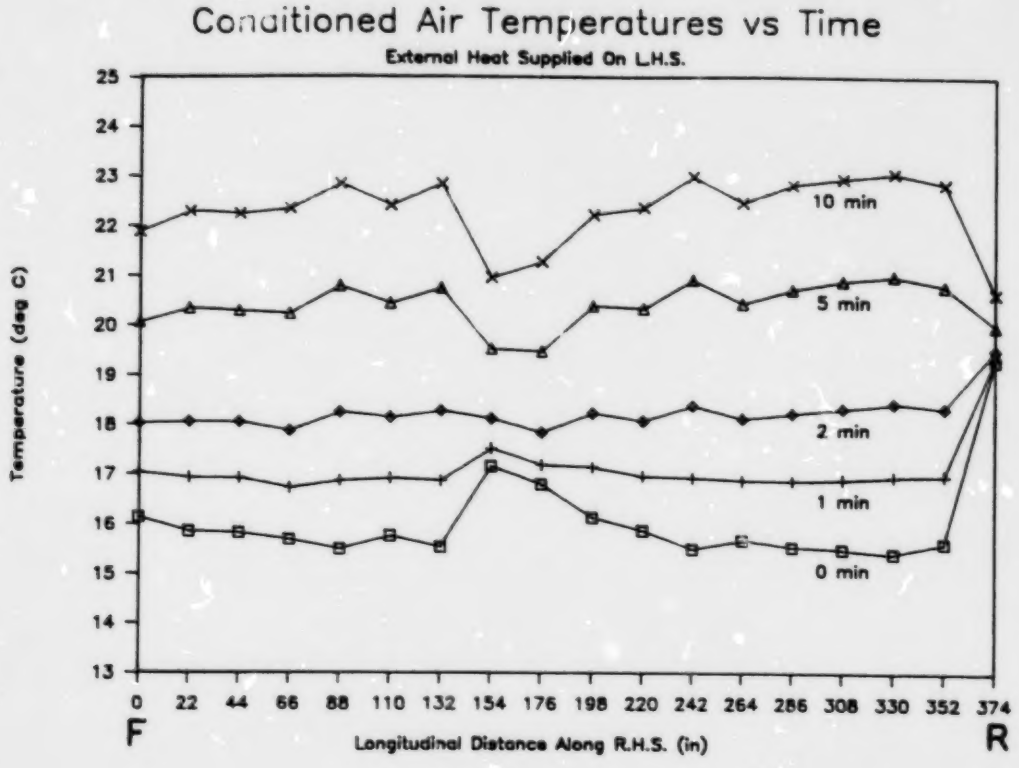


FIGURE B15

Coach RHS Temperature Profiles (External Heat Source)

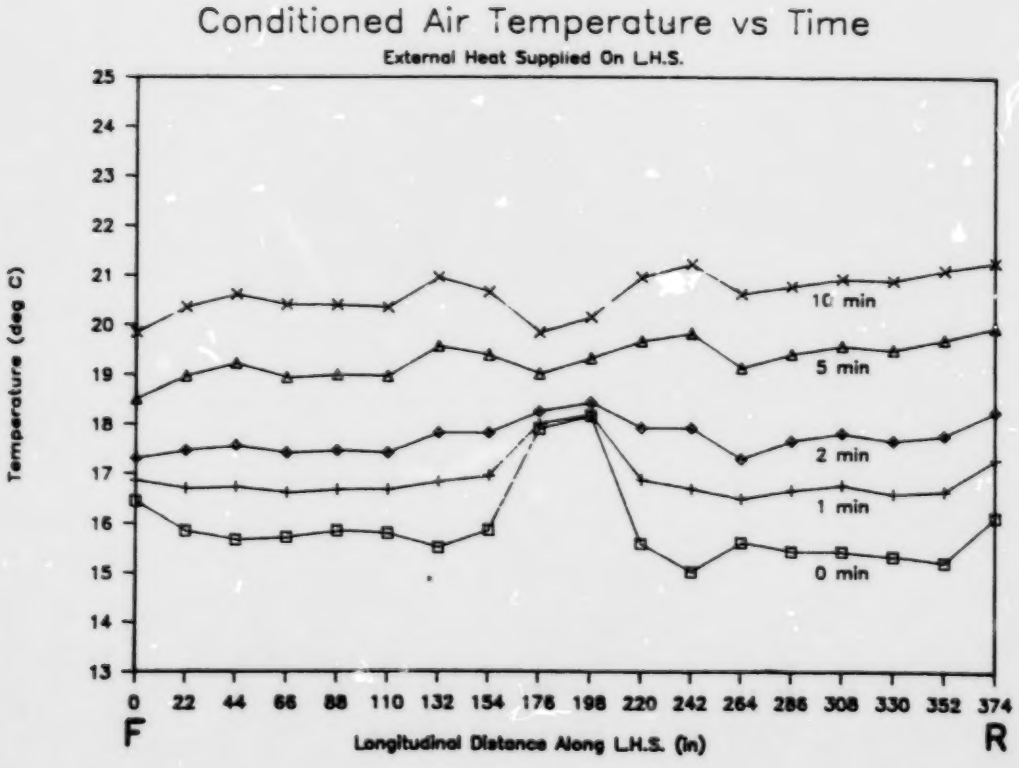


FIGURE B16

Coach LHS Temperature Profiles (External Heat Source)

CARBON DIOXIDE CONCENTRATIONS

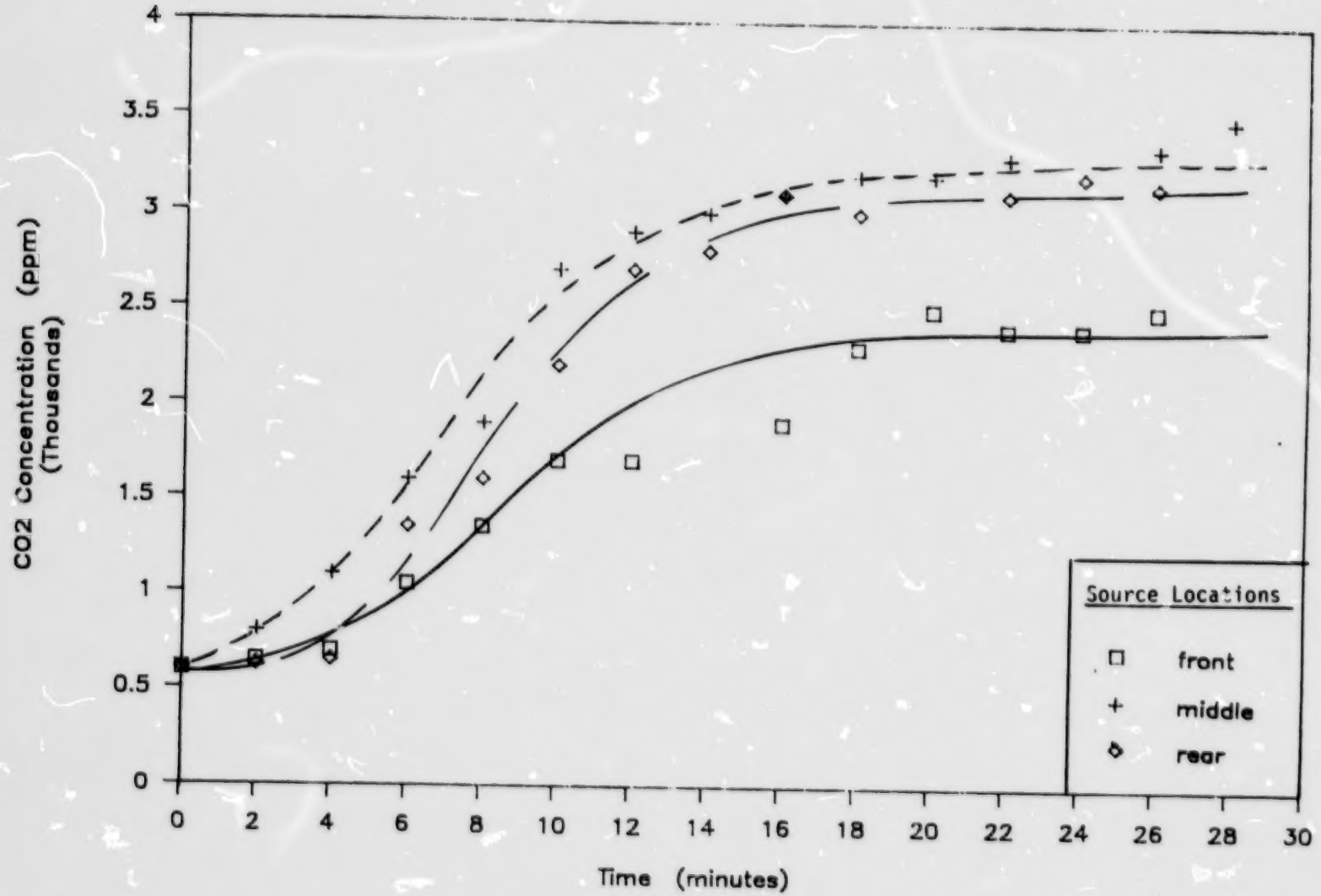


FIGURE B17

Carbon Dioxide Concentrations Versus Time

ANNEX C

Prévost Modification Kit Information

PREVOST®

SERVICE BULLETIN ☐ INFORMATION ■

SUJET / SUBJECT: VENTILATION DUCT

NO.: 86-02

APPLICATION: All «XL» coaches starting with V.I.N. 2P9L33406E1001638 to V.I.N. 2P9L3340XG1001063 included.

SECTION: 22

DATE: 04-86

DESCRIPTION:

It is now possible to increase the air flow to the central windows over the A/C blowers by proceeding with the following modification. This will slightly increase the noise level in the modified area, but ventilation will be much more uniform the length of the coach.

☐ NOTE:

This product improvement is not covered by the normal manufacturer's warranty.

MATERIAL:

One (1) ventilation duct parts kit #37-2176 including the following parts:

- Right deflector #37-2170
- Left deflector #37-2169
- Right perforated deflector #37-2168
- Left perforated deflector #37-2167
- Mineral wool #37-2175
- Mineral wool #37-2174
- 4 angles #37-2171
- 11 1/8" dia. S.S. rivets #50-4104
- 14 #8 x 1/2" lg. thd. cut screws #50-0654
- 1 installation diagram # D-370161

☐ NOTE:

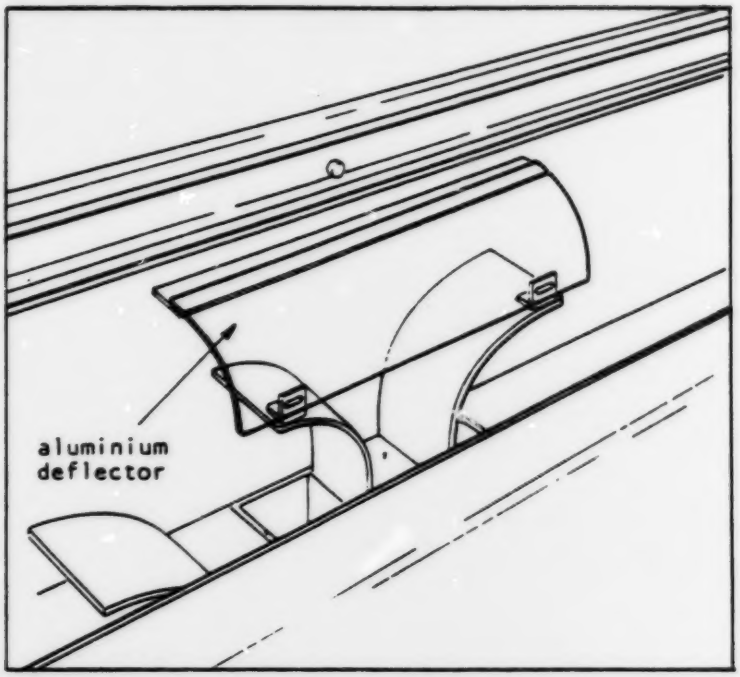
Parts must be ordered through regular channel.

PROCEDURE:

1- Remove the four foot long central ventilation ducts on both sides of the vehicle. (It may be necessary to remove some seats in order to remove the ducts).

2- Remove sponge rubber which is glued to the bracket welded to frame. (Refer to diagram)

3- Position temporaly aluminium deflector to match brackets with their slots, and mark bracket's position on existing deflector.



4- Using #50-0654 metal screws, install four #37-2171 brackets on upper ends of both air deflectors. (Use drill number 25, or 3,75mm (approx. 0.147 inches).

5- Using a wooder block to apply pressure, increase downward angle of bracket welded to the frame by 5 degrees.

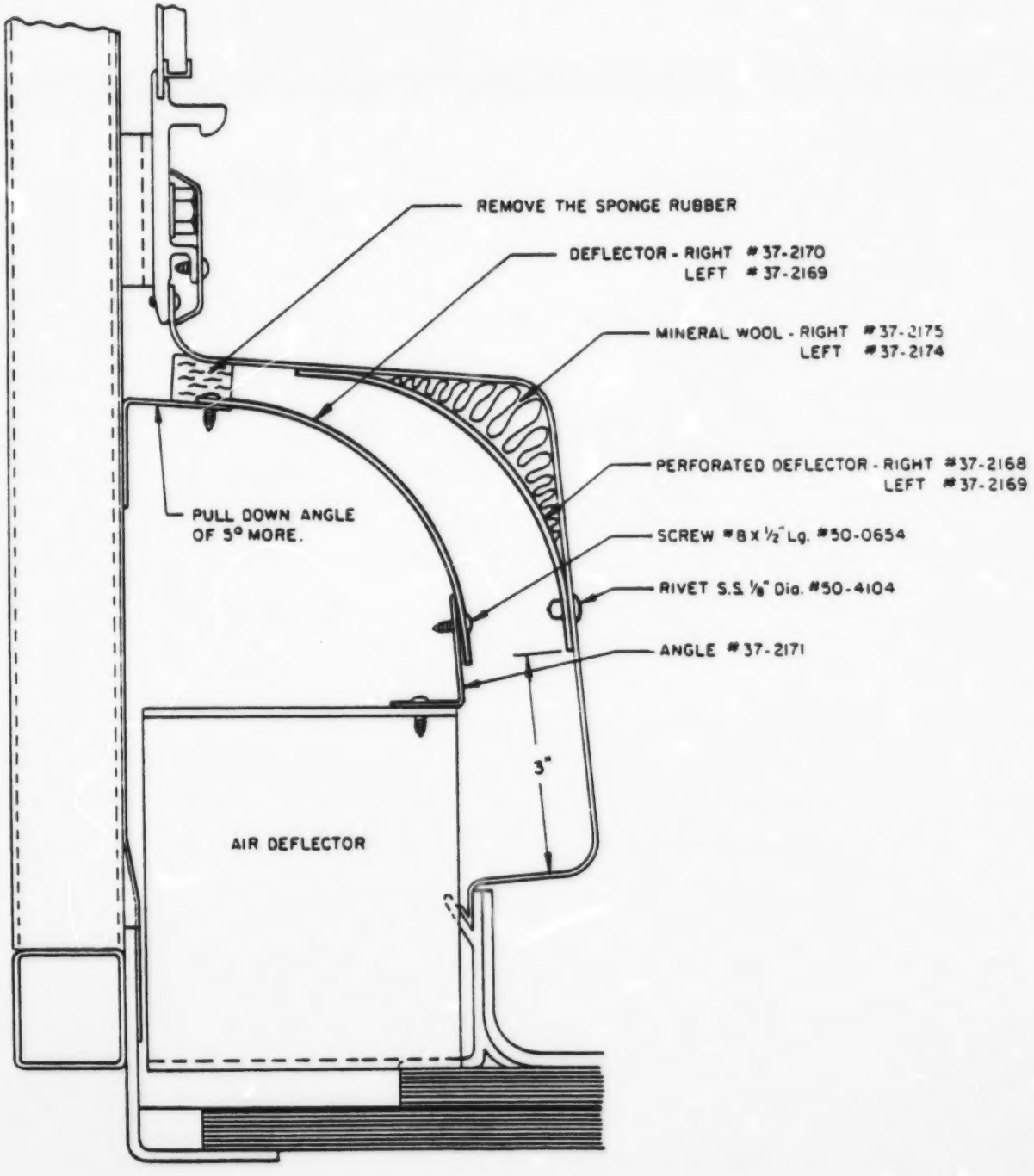
6- Using 2 new aluminium deflectors as templates, drill 0.147" diameter holes (3,75mm) on brackets welded to the frame, and brackets screwed to deflectors in step 4. (Refer to diagram).

7- Install #37-2170 deflector (21"long) to the right side of the vehicle, and #37-2169 deflector (15"long) to the left side. Use #50-0654 screws.

8- After having installed mineral wool (#37-2174 and #37-2175) as shown on diagram install the 2 perforated deflectors (#37-2167 and #37-2168) inside the 2 ducts removed in step one, and fix with #50-4104 1/8"dia. S.S. rivets.

9- Reinstall left and right ducts using the same metal screws.

INSTALLATION DIAGRAM



APPENDIX B

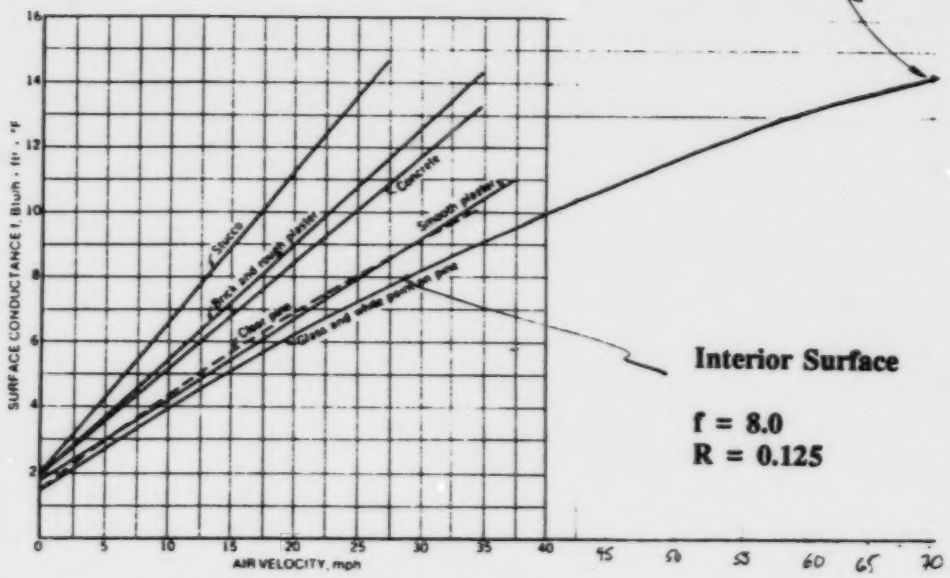
HEAT TRANSFER COEFFICIENTS
INTER-CITY COACHES

	THERMAL RESISTANCE/CONDUCTANCE						
	Wall (R)	Wall Framing (R)	Roof (R)	Roof Framing (R)	Floor (R)	Single Glass (R)	Double Glass[2] (R)
Exterior Surface[1]	0.07	0.07	0.07	0.07	0.68	0.07	0.07
Aluminum Skin	-	-	-	-	NA[3]	NA	NA
1" Fibreglass/Air Space	4.0	-	4.0	-	NA	0.11	0.69
Aluminum Inside	-	-	-	-	NA	NA	NA
Air Velocity in Duct or on Glass[1]	0.125	0.125	NA	NA	NA	0.125	0.125
½" Pine Floor	NA	NA	NA	NA	0.63	NA	NA
Still Air Inside Bus	NA	NA	0.68	0.68	0.68	NA	NA
TOTALS	**4.195**	**0.195**	**4.75**	**0.75**	**1.99**	**0.31**	**0.88**
CONDUCTANCE (U)	**0.24**	**5.13**	**0.21**	**1.33**	**0.50**	**3.28**	**1.13**

NOTES:
(1) See entrapolated curve for glass in Figure B-2.
(2) Insulating double glass, 3/16" air space.
(3) NA indicates not applicable.

Exterior Surface

f = 14.3
R = 0.007



Interior Surface

f = 8.0
R = 0.125

Surface Conductance for Different 12-inch

Square Surfaces as Affected by Air Movement

SOLAR LOADS

ROOF: Maximum $\triangle T$ for solar load for steel sheet with 1" insulation without suspended ceiling is 78° F

$\triangle T$ used calculation 15° F

difference 63° F

Additional cooling load per ft² : $63 \times 0.21 = 13.23 \frac{Btu}{hr.ft^2}$

at framing: $63 \times 1.33 = 83.79 \frac{Btu}{hr.ft^2}$

WALLS: Maximum $\triangle T$ 26° F

$\triangle T$ used in calculation 15° F

Difference 11° F

Additional cooling load per ft² : $11 \times 0.24 = 2.64 \frac{Btu}{hr.ft^2}$

at framing: $11 \times 5.13 = 56.43 \frac{Btu}{hr.ft^2}$

WINDOWS: 6 mm, 3/16" Air Space, 6 mm: Shading Coefficient of 0.40

½" Lucite: Shading Coefficient of 0.52 Use Worse Case

Sunny Side:	216 x 0.52 =	112 Btu/(hr.ft²)
Shady Side:	46 x 0.52 =	24 Btu/(hr.ft²)

HEATING AND COOLING

LOAD CALCULATIONS

ITEM	UNITS	MCI MC-9	MARATHON XL	
1. AREAS				
Roof:	(ft^2)	300	320	
Plus Framing @ 5%	(ft^2)	15	16	
Walls:	(ft^2)	260	206	
Plus Framing @ 5%	(ft^2)	13	10	
Windows:				
Double Glazed	(ft^2)	208	265	
Single Glazed	(ft^2)	28	29.5	
Floor:	(ft^2)	300	320	
2. SUMMER HEAT GAIN				
Calculations based on T = 15° F				
Humidity in bus @ 60% RH				
Bus speed 70 mph				
CONDUCTION: (ΔT x U x Area)				
Roof: 15 x 0.21 x Area	(Btu/hr)	945	1,008	
At Frame: 1 5 x 1.33 x Area	(Btu/hr)	299	319	
Walls: 15 x 0.24 x Area	(Btu/hr)	936	742	
At Frame: 15 x 5.13 x Area	(Btu/hr)	1,000	770	
Windows: 15 x 1.13 x Area	(Btu/hr)	3,526	4,492	
15 x 3.28 x Area	(Btu/hr)	1,378	1,451	
Floor: 15 x 0.5 x Area	(Btu/hr)	2,250	2,400	
SUB-TOTAL	(Btu/hr)	10,334	11,182	(1)

HEATING AND COOLING

LOAD CALCULATIONS

ITEM	UNITS	MCI MC-9	MARATHON XL	
SOLAR: (From Page B-3 x Area)				
Roof: 13.23 x Area	(Btu/hr)	3,969	4,233	
At Frame: 83.79 x Area	(Btu/hr)	1,257	1,341	
Walls: 2.64 x Area	(Btu/hr)	686	544	
At Frame: 56.43 x Area	(Btu/hr)	734	564	
Windows: 112 x Area x ½	(Btu/hr)	11,648	14,840	
24 x Area x ½	(Btu/hr)	2,496	3,180	
SUB-TOTAL	(Btu/hr)	20,790	24,702	(2)
VENTILATION:				
47 Passengers @ 15 CFM ea. 700 x 4.5 x 6.04 (Latent and sensible)	(Btu/hr)	19,026	19,026	
SUB-TOTAL	(Btu/hr)	19,026	19,026	(3)
INTERNAL LOADS:				
47 People 47 x 420 (Latent and sensible)	(Btu/hr)	19,740	19,740	
SUB-TOTAL	(Btu/hr)	19,740	19,740	(4)
SUMMER HEAT GAIN TOTAL (1)+(2)+(3)+(4)	(Btu/hr)	69,890	74,650	
	(tons)	5.82	6.22	

ITEM	UNITS	MCI MC-9	MARATHON XL
3. WINTER HEAT LOSS (BUS CRUISING)			
Calculations based on $\triangle T = 90^{\circ}F$ Bus speed: 70 mph			
CONDUCTION: ($\triangle T \times U \times$ Area)			
Roof: 90 x 0.21 x Area	(Btu/hr)	5,670	6,048
At Frame: 90 x 1.33 x Area	(Btu/hr)	1,796	1,915
Walls: 90 x 0.24 x Area	(Btu/hr)	5,616	4,450
At Fr[illegible]: 90 x 5.13 x Area	(Btu/hr)	6,002	4,617
Windows - Double: 90 x 1.13 x Area	(Btu/hr)	21,154	26,951
- Single: 90 x 3.28 x Area	(Btu/hr)	8,266	8,782
Floor: 90 x 0.50 x Area	(Btu/hr)	13,500	14,400
SUB-TOTAL	(Btu/hr)	62,004	67,163
VENTILATION:			
700 ft^3/min. x 1.08 x 90°F	(Btu/hr)	68,040	68,040
WINTER HEAT LOSS BUS CRUISING TOTAL		130,044	135,203

ITEM	UNITS	MCI MC-9	MARATHON XL
4. WINTER HEAT LOSS (BUS STOPPED)			
Calculations based on △T = 90°F Bus speed: 0 mph, Different R Factors Listed			
CONDUCTION: (△T x U x Area)			
Roof: R = 4.85, U = 0.206, 90 x 1.176 x Area	(Btu/hr)	5,562	5,933
At Frame: R = 0.85, U = 1.176, 90 x 1.176 x Area	(Btu/hr)	1,588	1,693
Walls: R = 4,295, U = 0.233, 90 x 0.233 x Area	(Btu/hr)	3,966	3,051
At Frame: R = 0.295, U = 3.390, 90 x 3.390 x Area	(Btu/hr)	3,966	3,051
Windows: - Double Glazed: R = 0.98, U = 1.020 - Single Glazed: R = 0.41, U = 2.439			
D: 90 x 1.020 x Area	(Btu/hr)	19,094	24,327
S: 90 x 2.439 x Area	(Btu/hr)	6,146	6,476
Floor: 90 x 0.50 x Area	(Btu/hr)	13,500	14,400
SUB-TOTAL	(Btu/hr)	55,308	60,200
VENTILATION:			
700 ft^3/min. x 1.08 x 90°F	(Btu/hr)	68,040	68,040
WINTER HEAT LOSS BUS STOPPED TOTAL	(Btu/hr)	123,348	128,240